The Role of the Forest Service in Aquatic Invasive Species Research

Susan B. Adams[1], Kelly M. Burnett[2], Peter Bisson[3], Bret Harvey[4], Keith H. Nislow[5], Bruce E. Rieman[6], and John Rinne[7]

Abstract

Aquatic ecosystems include the most imperiled taxa in the United States, and invasive species are the second leading contributor to this imperilment. The U.S. Department of Agriculture (USDA), Forest Service is legally mandated to sustainably manage aquatic habitats and native species on National Forest System (NFS) lands. Invasive species add complexity and uncertainty to natural resource management, and, thus, invasive species research is needed to guide effective, science-based management of aquatic systems. Although Forest Service Research and Development (R&D) scientists have much expertise to apply, aquatic invasive species research has not been an agency focus. We identify areas in which the Forest Service is well positioned to contribute research that other organizations are not addressing. Increasing agency emphasis on aquatic and riparian invasive species research and adding expertise in several areas (e.g., risk assessment, genetics, and several taxonomic areas) would facilitate a shift toward the Forest Service providing more valuable science and leadership in this arena. We identify some key general research needs; however, a more formal process, bringing Forest Service aquatic and riparian scientists together, perhaps with key NFS biologists and other stakeholders, is necessary to effectively identify and prioritize specific research needs. Some of the top research needs we identify include the following:

- Develop new prediction and ecological risk assessment tools and conduct risk assessments for priority invasive species and habitats.
- Collaborate on or establish a central data management repository.
- Increase understanding of ecological, physical, and biological factors facilitating and inhibiting invasions.
- Develop new prevention, eradication, and control tools.
- Enhance role of social sciences in aquatic invasive species research.
- Improve communications. Bring Forest Service R&D scientific expertise to bear on aquatic invasive species policy and regulation. Improve communication with NFS and other biologists and the public.

Importance of Aquatic and Riparian Invasive Species

Aquatic and riparian-associated species constitute the Nation's most imperiled biota, with the five most imperiled groups residing in freshwater and riparian habitats (fig. 1). Invasive species are the second most important factor in this imperilment, contributing to the declines of about one-half of the imperiled species (fig. 2). Invasive species can harm native communities via competition, predation, hybridization, and habitat alteration and as sources and vectors of alien pathogens. Species invasion is a global problem, and an international perspective is necessary to effectively address many invasion issues.

[1] Research Fisheries Scientist, Forest Service, Southern Research Station, Center for Bottomland Hardwoods Research, 1000 Front Street, Oxford, MS 38655.

[2] Research Fisheries Biologist, Forest Service, Pacific Northwest Research Station, Aquatic and Land Interactions Program, 3200 SW Jefferson Way, Corvallis, OR 97331.

[3] Research Fisheries Biologist, Forest Service, Pacific Northwest Research Station, Aquatic and Land Interactions Program, 3625 SW 93rd Avenue, Olympia, WA 98512.

[4] Research Fisheries Biologist, Forest Service, Pacific Southwest Research Station, Watershed Project, 800 Buchanan Street, Arcata, CA 95521.

[5] Research Fisheries Biologist, Forest Service, Northern Research Station, Fish and Wildlife Habitat Relationships in New England Forested Ecosystems, 201 Holdsworth NRC, University of Massachusetts, Amherst, MA 01003.

[6] Emeritus Research Fisheries Scientist, Forest Service, Rocky Mountain Research Station, Boise Aquatic Sciences Laboratory, 322 East Front Street, Suite 401, Boise, ID 83702.

[7] Research Fisheries Biologist, Retired, Forest Service, Rocky Mountain Research Station, SW Forest Science Center, 2500 South Pine Knolls Drive, Flagstaff, AZ 86001.

Figure 1.—*Degree of imperilment of various plant and animal groups* (*redrawn from Master et al. 2000*).

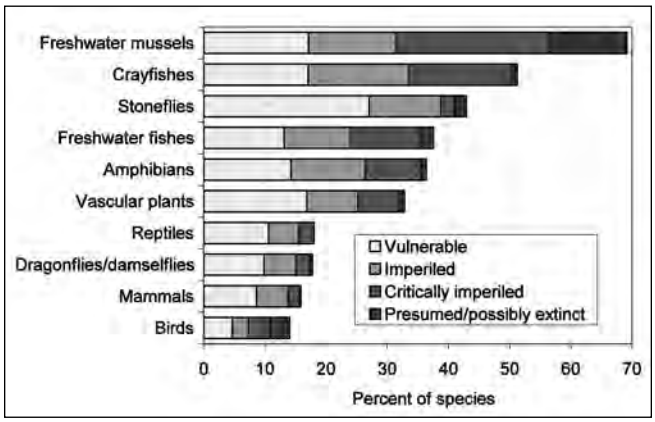
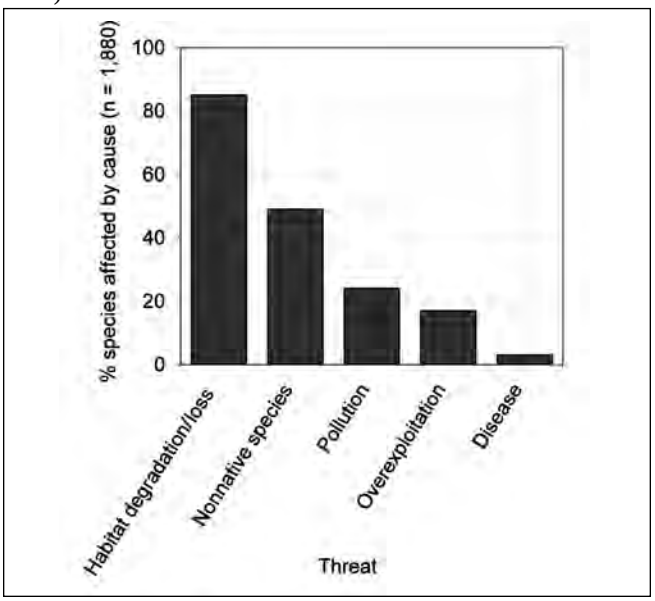


Figure 2.—*Causes of imperilment of imperiled and federally listed species in the United States* (*redrawn from Wilcove et al. 2000*).



Forest Service Mandate To Address Aquatic and Riparian Invasive Species Issues

The external panel (hereafter, "the Panel") charged with reviewing the Forest Service Research and Development (R&D) Invasive Species Strategic Program Area stated, "The mandate of the Forest Service (FS) and its current commitment to management of aquatic habitats is unclear from the briefing materials" (Raffia et al. 2006). Although perhaps not articulated to the Panel, a clear legal mandate for the Forest Service to manage aquatic habitats is conferred by three key laws—the Forest Service Organic Administration Act of 1897, the Multiple-Use Sustained-Yield Act of 1960, and the National Forest Management Act of 1976. These laws state that national forests are to be established and administered to secure favorable conditions for water flows and to provide the American people with multiple uses and sustained yields of renewable resources, including those related to watersheds, wildlife, and fish. Furthermore, under the Clean Water Act of 1977 and the Endangered Species Act (ESA) of 1973, Federal agencies are to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" and to ensure that actions they "authorize, fund, or carry out must not jeopardize the continued existence of any listed species or result in the destruction or adverse modification of critical habitat." USDA policy directs the Forest Service to "maintain viable populations of all native wildlife, fish, and plant species in habitats distributed throughout their geographic range on NFS lands" (USDA Forest Service 1995).

Forest Service R&D is directed to provide technical assistance to the National Forest System (NFS) in meeting its legal mandates as well as to other managers (other Federal agencies, tribes, States, and private landowners) of the Nation's 731 million acres of forested lands. As manager of 192 million acres of national forests and grasslands, which include 2 million acres of lakes, 300,000 miles of perennial streams, 200,000 miles of fishable streams, and 42 million acres of municipal watersheds, the Forest Service can influence the introduction, establishment, and spread of aquatic and riparian invaders through its policies, as well as by leadership in habitat management actions to control unwanted invaders. In the Western United States, roughly 75 percent of all water originates on NFS lands; thus, the Forest Service has a strong influence on the Nation's water resources. Water issues are a prominent and increasing part of the agency's interests, and invasive species can have a major influence on water quality, water availability, and aquatic biological integrity. Following are some regional examples of

the threats that aquatic and riparian invasive species pose to the Nation's aquatic resources on Federal lands.

The *Interior Columbia River Basin* has 88 recognized native taxa of fishes and 55 nonnative taxa (Lee et al. 1997). Two introduced fishes are now the most widely distributed of any fish taxa (native or nonnative) in the basin. Roughly one-half of the native fishes are of conservation concern, due in large part to invasive species. Large, warm, low-elevation habitats are among the most invaded aquatic communities, but invasions continue to progress upstream. In many cases, spread of invasive species is facilitated by human activities (e.g., habitat alteration and fish stocking), but climate change and shifting hydrologic processes may extend or accelerate the process. In addition, many high-elevation lakes have been stocked with nonnative fishes.

In the *Southwestern United States*, reservoir construction and fisheries management have contributed to an irruption of aquatic invasions and subsequent imperilment of native fishes (Rinne 1996). For example, during the 20th century, more than one-half of the 100 nonnative fish species introduced in Arizona became established. Due to extensive modification of low-elevation rivers, most remaining perennial, riverine habitats are on NFS lands and serve as refugia for native species, 70 percent of which are listed under the ESA (Rinne and Medina 1996).

In the *South Atlantic-Gulf of Mexico* region (east of the Mississippi River) the U.S. Geological Survey (USGS) Nonindigenous Aquatic Species database indicates established populations of 226 nonnative aquatic species, 122 of which are not native to North America (USGS 2008). Nonnative sport fishes have displaced related, native species. Some of the 52 nonnative aquatic plant species have created major habitat changes and altered biological and physical ecosystem functions, leading to native species displacement and loss of recreational and commercial opportunities among other effects.

The *Great Lakes Basin* has more than 180 established, nonnative aquatic species and has the highest known invasion rate for a freshwater ecosystem; a new invader is discovered every 28 weeks, on average (Ricciardi 2006). High-profile species (e.g., sea lampreys and zebra mussels) cause large economic losses, but many other, less-publicized species also cause substantial ecological disruptions.

In the *Northeastern United States*, aquatic and riparian invasive species pose problems for major river and species restoration efforts. Nonnative fishes, in combination with habitat change, complicate the conservation and restoration of a suite of native diadromous fishes, including the last wild Atlantic salmon populations (listed under ESA) in the United States (National Research Council 2004). Invasive riparian plants (e.g., purple loosestrife and Japanese knotweed) threaten the success of ecological flow prescriptions designed to restore threatened floodplain forest communities (Nislow et al. 2002).

Roles of Forest Service Research and Development in Aquatic and Riparian Invasive Species Research

Past and Current Roles

The Forest Service R&D has not been a national leader in aquatic invasive species research, although Forest Service R&D scientists have conducted excellent research on some aquatic invasions. Despite the enormous threats invasive species pose to aquatic ecosystems, invasive species research within Forest Service R&D has focused primarily on weeds, insects, and diseases harmful to forests and rangelands. Overall, momentum and funding for Forest Service research on invasive aquatic and riparian species lag far behind those for invasive upland species.

Given the agency's lack of emphasis on and funding for invasive aquatic and riparian research, potential near-term program strengths are not necessarily reflected in research to date. The Forest Service R&D maintains a strong group of fish and aquatic ecologists who are well qualified to conduct invasive species research; indeed, most have researched invasive species at some time in their careers. Thus, if agency funding priorities were directed toward such work, Forest Service scientists would be well positioned to conduct research addressing aquatic invasive species.

Future Roles

The Panel concluded that Forest Service R&D on invasive species needs to be strengthened, administrative burdens on scientists reduced, and an independent scientific board established to advise administrators at the national level. We concur. However, we strongly disagree with the Panel's reluctance

"…to recommend increases in investment in aquatic habitat management at the risk of further weakening the traditional terrestrial-related FS research" (Raffa et al. 2006: 10).

Although other Federal agencies share responsibilities for addressing aquatic and riparian invasions, their management and research priorities generally differ from those of the Forest Service (table 1), making it essential for Forest Service R&D to participate in future research in this area. In one ongoing effort to prioritize risks from invasive species, for example, the lowest level of threat to which invaders are assigned is a "threat to ecosystem health" (NISC and ANSTF 2007); however, to land managers, ecosystem health is a high priority. Because of different priorities, minimal research can be expected by other Federal agencies on aquatic and riparian invasive species in headwater and high-elevation rivers where many public lands occur, an area in which Forest Service R&D expertise is recognized internationally. Further, in headwater systems, where terrestrial and aquatic ecosystem contact is maximized, the probability of establishment and effects of invasive species are likely to be most dependent on land management and upland habitat changes.

The Forest Service is in a position to conduct invasive species research over longer periods than the graduate student cycle typified by most academic research programs. Long-term research is necessary for developing control and eradication tools, monitoring effectiveness of control efforts, learning by adaptive management, and understanding how long-term changes (e.g., in climate or fire regimes) influence the spread and effects of invasive species. Long-term research is particularly relevant in aquatic systems because aquatic population and habitat responses to many land management actions may lag significantly behind those in terrestrial systems. Thus, identifying influences of upland habitat alteration on the vulnerability of aquatic habitats to invasion requires long-term study.

Forest Service R&D is poised to address aquatic and riparian invasive issues on regional, national, and international scales through long-term partnerships that scientists have established

Table 1.—*Roles of other selected Federal agencies in aquatic invasive species research and management.*

Program	Area of invasive species responsibility
U.S. Department of the Interior	
U.S. Fish and Wildlife Service, ANSTF[1]	Cochair of ANSTF. Employs an ANS Coordinator in each region. Directs funding to regional ANSTF panels. Works with States to develop State ANS plans.
USGS, Science Centers and Cooperative Education Units	Conducts research on invasive aquatics and riparian plants, but focuses primarily on large rivers and wetlands at low elevations. Includes research support for Department of Interior lands. Maintains national invasive species databases.
Bureau of Reclamation	Conducts research on control and monitoring of aquatic and riparian invasive species, primarily in large, regulated rivers.
NOAA	
ISP	Cochair of ANSTF. Supports research on invasive species issues related to marine, estuarine, and diadromous organisms and introductions via marine pathways, such as ballast water introductions.
NCRAIS	Fosters cross-NOAA leadership, communication, and coordination for NOAA's research investments in support of understanding, preventing, responding to, and managing aquatic species invasions in U.S. coastal ecosystems (including the Great Lakes ecosystem).
USDA APHIS	
National Wildlife Research Center	Conducts research on aquatic invasive species but places priorities on birds, mammals, wildlife diseases, and aquatic plants.
U.S. Department of Defense	
U.S. Army Corps of Engineers	Conducts research and control studies on aquatic invasive plants.

ANS = aquatic nuisance species. ANSTF = Aquatic Nuisance Species Task Force. APHIS = Animal and Plant Health Inspection Service. ISP = Invasive Species Program. NCRAIS = National Center for Research on Aquatic Invasive Species. NOAA = National Oceanic and Atmospheric Administration. USDA = U.S. Department of Agriculture. USGS = U.S. Geological Survey.

[1] *"The Aquatic Nuisance Species (ANS) Task Force is an intergovernmental organization dedicated to preventing and controlling aquatic nuisance species, and implementing … the National Invasive Species Act (NISA) in 1996. The task force consists of 10 Federal agency representatives and 12 Ex-officio members. The task force coordinates governmental efforts dealing with ANS in the United States with those of the private sector and other North American interests via regional panels and issue specific committees and work groups" (USFANSTF n.d.). Although not a member of the task force, the Forest Service is a member of some regional panels and committees.*

with (1) NFS biologists and botanists; (2) the national network of Forest Service research natural areas and experimental forests and ranges; (3) Forest Service International Programs; and (4) scientists working at long-term ecological research sites, National Ecological Observatory Network (NEON) sites, and other agencies, organizations, and universities. Because of its broad geographic scope, Forest Service R&D is in an excellent position to study species that are native in some parts of the United States and invaders in others (e.g., brook trout, rainbow trout, Atlantic salmon, and red swamp crayfish).

Customers for Forest Service Research on Aquatic and Riparian Invasive Species

The Forest Service aquatic research program, including invasive species research, has a broad customer base. Any organization or person interested in the conservation of aquatic biological diversity, aquatic ecological function, recreational and commercial fishing, and interactions between land management and invasive species is a potential customer.

Government customers in the United States (including Federal, State, local, and tribal natural resource management and regulatory agencies and other government entities and politicians) use Forest Service R&D aquatic invasive species research findings to inform decisions related to fish stocking, species conservation, and habitat management. Aquatic invasive species research by the Forest Service is also conducted and used internationally where similar invasion issues exist (e.g., rainbow trout in South America); international collaborations can be critical to our understanding of invasions in the United States (e.g., expertise from Australia and Central America regarding waterborne chytrid fungus causing mass mortality of amphibians in the United States).

All Forest Service branches (International Programs, State and Private Forestry [SPF], and NFS) use Forest Service R&D results on aquatic invasive species. International Programs, SPF, and Forest Service technology transfer professionals use the research results to inform landowners, recreationists, and other parties how to recognize aquatic and riparian invasive species and how to help minimize spread. Given that introduced species can arrive and spread on NFS lands via recreational activities, a better-informed public is essential to reducing spread of invasive species. NFS biologists and botanists have clear and immediate needs for Forest Service research on invasive species, both to manage ongoing invasions and to prevent future invasions. The latter is important because the introduction and spread of some aquatic and riparian invasive species have been facilitated by NFS activities such as road building, timber harvest in riparian areas, reforestation, firefighting (water transfers), erosion control measures (e.g., seeding or planting nonnative plants), stream and riparian restoration, stocking nonnative game fish, and providing motorized recreation access (e.g., campgrounds and boat launches).

Nongovernmental users of Forest Service R&D research include academic scientists, nongovernmental organizations focused on aquatic conservation or natural resource management, professional societies, fishing clubs, and the public, including rural communities. A shift to more urbanized customers may alter demands on natural resources, expanding emphases on clean water and nonconsumptive recreational uses from NFS lands and influencing research priorities on invasive species.

Key Future Aquatic and Riparian Invasive Species Research Issues

The key future research issues regarding aquatic and riparian invasive species fall into two general categories: (1) questions directly related to prevention, prediction, management, etc., of invasive species (addressed under subheadings below), and (2) conservation and ecosystem management questions to which threats from invasive species add new complexity. The latter includes understanding how invasions influence the probability of persistence for native species, defining the potential roles of public lands in providing refugia for native aquatic communities, and identifying and addressing conflicting resource management goals related to aquatic invasions.

Federally managed lands serve as refugia for many species. Aquatic and riparian invasions have typically proceeded upstream from low-elevation habitats and so have contributed substantially to the functional fragmentation of aquatic networks. Consequently, many native species persist only in isolated remnant populations in headwater systems, intensifying their susceptibility to extinction. As fragmentation increases,

forest management will become even more critical to the conservation of remnant aquatic biological diversity. Identifying aquatic refugia and prioritizing them for protection is part of many conservation-planning processes. Identifying refugia that are less prone to invasion is important, because these areas will become the strongholds of biotic integrity and sources of colonists to repopulate newly restored, connected habitats. More research on invasion mechanisms of particular species and on habitat and biotic characteristics conferring resistance to invasion would facilitate conservation planning. We predict an increased need for Forest Service research related to managing habitats and populations fragmented by nonnative species. Many requests for invasive species research are driven by the ESA (e.g., threats of invaders to ESA-listed aquatic fauna), which will continue to strongly influence management and, thus, research priorities.

Many existing aquatic invasive species issues stem from conflicting goals and values within and among agencies and the public. Conflicts arising before introduction of a species (table 2) often relate to differences in values, assessments of risk, or willingness to accept invasion risk. For example, goals of game fish stocking to provide recreational fishing opportunities in wilderness lakes may conflict with goals of conserving rare species or of maintaining areas where natural processes predominate. Conflicts over management goals also arise after invasion (table 3) but may not be immediately apparent. The potentially complex tradeoffs between preempting and allowing nonnative trout invasions in mountain rivers illustrate this point. Constructing barriers to preempt invasion by a nonnative trout can isolate native trout populations, eliminating the expression of migratory life histories that may be key to their long-term persistence. Thus, society must sometimes choose between an isolated population of a native species that depends on active management for persistence or a nonnative form that may retain more resilience and fill a similar ecological role. Although scientific understanding alone will not resolve conflicts, it can help society answer the tough questions related to invasive species issues. Forest Service R&D has and can continue to provide science that informs the discussion of conflicting goals by distinguishing facts from values in the decisionmaking process, illuminating conflicting goals, and predicting outcomes, risks and tradeoffs of various management activities related to aquatic invasions. Forest Service R&D research on high mountain lake fish stocking provides a good model of research constructively contributing to addressing conflicting goals.

Table 2.—*Examples of conflicting goals with respect to human activities potentially leading to intentional species introductions.*

Goals favoring native ecosystems	Goals favoring potentially invasive species
Conserve native biodiversity/ecological integrity (conservation of threatened and endangered species).	Recreation—game fish stocking, use of live bait, motorized vehicle/boat access.
Wilderness values—maintenance of natural processes (includes legal mandates).	Agriculture—species importation for aquaculture or for control of other organisms (e.g., mollusks in fish farming), live food trade.
Protection of existing commercial interests (e.g., commercial fishing for native species or tourism).	Commerce—importation or transfer of species for pet and nursery trades.

Table 3.—*Examples of conflicting resource management goals after invasion.*

Eradicate or control invasive species		Maintain or promote invasive species
Restore native community.	⟷	Ongoing fish stocking for recreation.
Install barriers to halt invasion—persistence of native species only with active management.	⟷	Maintain/restore connectivity and allow invasion—persistence of nonnative with similar ecological function without need for active management.
Use of chemicals to eradicate invasive species—risk to some nontarget native organisms, public health concern.	⟷	No chemical use—persistence of nonnative, reduced risk to some nontarget organisms.
Economic—restore commercial interests based on native species (commercial harvest, tourism, etc.).	⟷	Economic—maintain economic value from invasive species (aquaculture, recreation).

Prevention and Prediction

Although prevention is not easily tallied in annual accomplishment reports, it is the most effective tool for countering invasive species. Prevention of aquatic invasive species requires attention at three scales: (1) keeping new invasive species out of North America, (2) preventing invasions across natural boundaries (e.g., among river basins), and (3) preventing the spread of invasive species to new habitats within river basins. Forest Service R&D has played a role in the latter by researching and providing guidance to managers on the tradeoffs of installing instream barriers to prevent upstream invasions. Also, Forest Service R&D participated in developing effective methods and guidelines for cleaning equipment used in firefighting and other activities to limit spread of aquatic invasive species. Forest Service R&D can play a bigger role in the first two scales both via research (e.g., risk assessments) and by informing policy decisions made by other agencies (e.g., the Animal and Plant Health Inspection Service and the U.S. Fish and Wildlife Service) on intentional importation and interdrainage transfers of live aquatic and riparian organisms. The Forest Service participates in some networks addressing such issues (e.g., GLRC 2005: appendix A), but coordinated efforts vary regionally.

Prediction of possible outcomes resulting from nonnative aquatic species invasions is a high priority need that Forest Service R&D can help meet by developing ecological risk assessment tools. Risk assessment components are most useful when developed in the context of an interactive, computer-based decision support system that can be readily accessed by risk assessors and risk managers to (1) describe and understand the current distributions (sources) of aquatic invasive species; (2) predict the future establishment, spread, and consequences of aquatic invasive species based on species characteristics, aquatic habitat and biotic community characteristics, and potential pathways of spread; (3) identify locations where control technologies may efficiently limit the spread of aquatic invasive species; and (4) evaluate the overall effectiveness and net benefits afforded by alternative control measures proposed for specific locations. Risk assessments on aquatic invasive species for NFS lands are likely to include local vectors more than the international trade and transportation vectors emphasized as key sources of introduced aquatic organisms to the continental United States (Lodge et al. 2006). Improved understanding of invasions in the ecological context of habitat conditions (e.g., Brown and Moyle 1997, Harvey et al. 2004) will be critical for effective risk assessments. A long-term strength of Forest Service R&D has been discovering the ecological roles of natural and anthropogenically influenced disturbance regimes (fires, floods, insect outbreaks, etc.). Therefore, Forest Service R&D is well positioned to address how modification of disturbance regimes influences invasion probability and susceptibility.

Detection and Eradication

The Panel accurately noted that biological monitoring on NFS lands is weak for early identification of aquatic and riparian invasions. Few, if any, national forests have monitoring programs designed to detect an array of potential aquatic or riparian invaders. The probability of detecting aquatic nonnatives early in an invasion varies by region, depending on the number of aquatic and riparian biologists working in the area, the level of public awareness, and the diversity of potential invaders and native aquatic and riparian biota. High biodiversity in the Eastern United States, coupled with relatively few aquatic specialists, reduces the probability of an invasive taxon being recognized as nonnative. For some taxa (e.g., crayfish), complete ranges of many native species are not known, further compounding the difficulty of recognizing invasions. Both information transfer experts and field biologists need guidance in identifying organisms that should be the foci of their efforts. Forest Service R&D can assist by doing the following:

1. Developing regional lists of potential invasive aquatic and riparian species.
2. Creating or contributing to taxonomic guides and voucher specimen collections.
3. Collaborating to train NFS biologists and other partners to detect invasive species.
4. Developing a sentinel strategy, including identifying sites where introductions are most likely to occur and developing rapid survey protocols for monitoring these sites, increasing the likelihood of detecting new invasions while populations are small, localized, and still vulnerable to eradication.

Eradication of aquatic invasive species is often difficult or impossible over large areas but may be successful as part of a targeted rapid response to incipient aquatic invasions. Active control measures for aquatic invasive species have been criticized as costly, ineffective, and damaging to some native plants and animals. Research to better determine impacts of

existing control measures, to develop mitigation strategies, and to evaluate alternative control measures may be of great interest to Forest Service R&D customers. This research area is one of potential strength for Forest Service R&D, in part because NFS biologists and Forest Service engineers (e.g., in the San Dimas and Missoula Technology and Development Centers) can participate in developing and implementing experimental control measures over long periods.

Passive control methods associated with maintaining and restoring natural hydrologic and thermal regimes may be far more effective and efficient than active control with respect to many invaders, but research is needed to better understand conditions under which passive control is effective. Invasive fish, aquatic invertebrates, and riparian plants often establish and thrive in altered or degraded habitats. Research focused on natural processes constraining the distribution of invasive species at local and regional scales (e.g., predictive models above) could lead to more efficient control measures.

Management and Mitigation

In most cases, attention to invasive aquatic and riparian species in the Forest Service has been inadequate for developing effective management options. Lack of understanding about the full range of ecological effects of specific invasive aquatic and riparian species on native plants and animals limits abilities to develop effective, science-based management options. Forest Service R&D could play an important role in providing basic ecological knowledge about invasive species and their effects.

Research is needed to better understand, manage, and mitigate effects of invaders across terrestrial-aquatic boundaries. Forest Service R&D results illustrate that nonnative fish introductions in high-elevation lakes can lead to food web effects that influence terrestrial wildlife. Similarly, terrestrial invaders can influence aquatic communities. Nonnative feral pigs alter stream invertebrate and microbial communities and increase pathogen levels (Kaller and Kelso 2006) and stream nitrate concentrations (Singer et al. 1984). Invasive riparian plants pose substantial threats to native aquatic species and may dramatically alter ecosystem functioning (Richardson et al. 2007), but research is just beginning in this area. Despite their potential threat, invasive riparian plants have received relatively little attention.

Restoration and Rehabilitation

Large amounts of money are spent nationally to restore aquatic habitats, typically with the ultimate goal of recovering or reestablishing native aquatic fauna. In some cases, invasive species have immediately colonized and thrived in the restored habitat, rendering the restoration unsuccessful for conservation purposes. To better prioritize funds for habitat restoration, research is needed to predict the circumstances under which restored habitats are likely to be invaded. Because of Forest Service involvement in restoration, this role is a logical one for Forest Service R&D.

Application and Communication

Responding quickly to new invasive species increases the probability of eradication and can minimize negative ecosystem effects. The Forest Service does not have a coordinated strategy to identify, rapidly respond to, and prioritize invasive aquatic and riparian species threats and research needs at national or regional levels. “Outbreaks” are typically managed at the local level without the benefit of regionwide coordination and technical information transfer. In addition to needing intra-agency coordination, the Forest Service needs mechanisms in place for rapid communication with external scientists. NFS or Forest Service R&D representation on Aquatic Nuisance Species Task Force regional panels or research prioritization committees may be an effective means for meeting this need, while also serving as a means for Forest Service scientists to become more familiar with regional invasive species issues and the people working on them. Forest Service R&D also needs to improve communication with regulators and policymakers involved in invasive species issues.

Because of close interaction with a national network of NFS biologists and botanists, Forest Service research scientists are well positioned to both obtain information from and provide research results to the field. Formalizing these relationships with regard to invasive species information may encourage and facilitate such communication.

Top Research Needs

The following list enumerates some important general research needs, but prioritization of specific research needs, although important, will require a more thorough and inclusive approach than our timeline has allowed. If Forest Service R&D increases emphasis on aquatic and riparian invasive species

research, the first steps should be a thorough inventory of institutional capacity to conduct such research, followed by a more systematic regional or national prioritization of aquatic invasive species research needs. The prioritization can be based on existing knowledge but should follow a formal process. Participants can be expected to include scientists from a broad range of disciplines (e.g., hydrology and geomorphology as well as stream ecology and fish biology) and NFS managers and professionals knowledgeable about aquatic and riparian invasive species issues.

Within the stated context, we offer the following eight top general research needs.

1. Develop new prediction and ecological risk assessment tools essential for helping decisionmakers prioritize which invasive species to address, what actions to take, and where to take them. In many cases, useful data exist, emerging statistical approaches offer greater power than ever before, and decision support and prioritization frameworks are available for consistent analysis and effective communication. Despite these available resources, developing ecological risk assessment tools will require a substantial investment in new data and models to predict probable invasions, species interactions, and ecological outcomes. Initial modeling efforts can focus on potential and established invaders that appear to pose the most serious risks. Effective prediction and prioritization must be conducted in the context of large-scale influences. Fire, climate change, and changing forest community composition are clearly important cross-cutting issues because changing environments will alter the constraints on species distributions.
2. Contribute to building and maintaining state-of-the-art, centralized data repositories. This action is critical for documenting species spread and for risk assessment and model development. Forest Service R&D can collaborate with the NFS and with other agencies already managing aquatic and riparian invasive species data. Examples of existing national databases are those maintained by the USGS Nonindigenous Aquatic Species program in Gainesville, FL, and by the USGS National Institute of Invasive Species in Fort Collins, CO. Biologists and fire personnel, however, often require distribution data at finer spatial scales than are now available to map invasive species occurrences at district or more local levels.
3. Increase awareness and investigation of the interaction between global climate change and aquatic invasive species. Conduct research on linkages between region-specific climate projections and invasion risk and on synergistic effects of climate change and nonnative species on native communities.
4. Improve understanding of ecological, physical, and biological factors facilitating and inhibiting invasions. Encourage research to move beyond *species-habitat relationships* toward investigations of *species interactions* (which is key to understanding effects of invasive species) as influenced by habitat and disturbance. Examine effects of invasions on ecosystem functions.
5. Increase multiscale research to better understand and model the hierarchy of controls on invasions. For example, an effective research approach to large-scale invasions may be to explore invasion patterns and associations at a variety of scales to develop hypotheses regarding controls, conduct mechanistic research at appropriate scales, and then reaggregate results for prediction across scales.
6. Develop more effective prevention/eradication/control measures, and use risk assessment tools for weighing the potential benefits versus deleterious effects on native species.
7. Enhance the roles of social sciences and economics in aquatic invasive species research. For example, understanding conflicting public values is important in developing valid risk analyses and successful control strategies for aquatic and riparian invasive species. Evaluating the efficacy of different outreach strategies can identify tools that increase public motivation and, thus, compliance with preventative measures. Accounting for the full costs of species invasions will be instrumental for informing the public and policymakers of potential societal effects from nonnative species and, thus, for adopting effective prevention and control strategies.
8. Improve communication of invasive species science among scientists, NFS managers, policymakers, and the public. Although not a research need *per se*, a need exists to bring Forest Service scientific expertise to bear on issues of policy and regulation aimed at preventing future aquatic and riparian invasions. Establish mechanisms for rapid participation *as an agency* to provide science-based input on questions of transporting species across national and natural boundaries.

Structuring Forest Service R&D for Effective Aquatic Invasive Species Research

Although issues surrounding aquatic and riparian invasions will certainly intensify, predicting specific issues is impossible. Thus, Forest Service R&D can be best prepared by maintaining broad expertise within a structure flexible enough to respond rapidly to new threats. The Panel noted a need to maintain broad taxonomic expertise, which Forest Service R&D could improve on. Our representation (in terms of numbers and distribution of positions) in fish ecology is strong in the West and somewhat weaker in the East, and our expertise in herpetology is scattered. Expertise in riparian and aquatic plants, mussels, crayfish, and aquatic insects is scarce in Forest Service R&D. The Forest Service can provide ecological and landscape scale research on invasive aquatic diseases and parasites, but collaboration with research organizations operating established disease laboratories would maximize efficiency. External collaborations will, of course, remain essential to our overall effectiveness in invasive species research.

Other disciplines are also necessary for a successful invasive species research program. Many aspects of aquatic ecological research, including invasion research, require expertise in genetics. Genetics work is currently accomplished primarily through external collaboration, but Forest Service R&D may consider the cost-effectiveness of increasing capabilities internally, as a national resource. Expertise in geographic information systems (especially with regard to stream networks), spatial analysis, epidemiological modeling, and risk assessment varies by research station, but is essential to developing predictive models and integrating invasive species data management for an effective aquatic invasive species research program.

Critical to quickly and cost-effectively responding to invasion issues is not overcentralizing expertise. Invasion issues are typically region specific; thus, addressing them depends on maintaining regional understanding and awareness. Because the aquatic research program is small and invasive species issues are numerous and often region specific, duplication of aquatic research effort is not a problem and likely will not become a problem within Forest Service R&D in the near future.

Having argued for dispersed expertise, we acknowledge that some skills may be in common demand nationally. For example, the suite of analytical and predictive tools for risk analysis and prediction of species habitat and occurrence might be collaboratively developed and maintained in a "center of excellence" but fed by data and research from all regions. For common species groups or guilds, developing common approaches could be powerful. Sharing knowledge and data for species that are native in one region and invasive in another could facilitate understanding of the primary constraints and development of the needed predictive models. In many cases, broad collaboration provides the foundation for understanding that may otherwise be impossible.

Scientists initiate most cross-station research efforts. Future collaboration could be fostered through national or multiregion panels, composed of Forest Service R&D scientists, NFS personnel, and other stakeholders, identifying important issues and then funding relevant research. Key challenges of predicting, preventing, and controlling invasive species may be best met by combining multistation teams of scientists who have local, spatially explicit knowledge of conditions and key processes. Teams could focus on (1) identifying and studying taxa that are important over large areas and (2) refining risk assessment models. These large-scale efforts would identify taxon- and context-specific needs for research on combinations of potentially invasive taxa and ecologically important resources.

A byproduct of national teams would be better communication among Forest Service aquatic scientists. Identifying particular expertise in aquatic science is difficult within the Forest Service. Mechanisms (e.g., a Web-accessible database) for locating Forest Service scientists with various skills related to invasive species would facilitate communication; however, we strongly agree with the Panel's caution about increasing the reporting burden on scientists.

Finally, we identified one of our strengths as the ability to do long-term research. This strength could be greatly improved by lengthening the research funding cycle or creating better mechanisms for funding long-term research.

Conclusions

Uncertainty will always be a major feature of invasive species science. Confronting uncertainty is important in both management and research and in communicating with stakeholders. Principles articulated by Ludwig et al. (1993) suggest that managers should favor decisions that are robust to uncertainty (i.e., the outcome is likely to be favorable regardless of the result). If that is not possible, it is still important to hedge (use a mix of strategies), favor reversible decisions, and intentionally probe ecosystems to learn through adaptive management (try some risky things for the sake of learning) (e.g., Fausch et al. 2006). The Forest Service has long advocated adaptive management but has seldom implemented it with true management experiments designed for learning (e.g., Bisson et al. 2003). Invasive species issues provide an opportunity for the marriage of research and management in the Forest Service that could be extremely important to future management.

Our society highly values aquatic recreation, clean water, and freshwater biodiversity. The future of all three components depends on strong research programs to address the ever-increasing threat of invasive species that can profoundly alter our waters and riparian areas. Thus, we deem it essential for the Forest Service to commit to a research program and infrastructure that will effectively address invasive aquatic and riparian species issues.

Acknowledgments

The authors thank Nick Schmal, Glen Contreras, Kate Dwire, Frank McCormick, Rich MacKenzie, Hart Welsh (Forest Service) and Jason Dunham (U.S. Geological Survey) for insightful discussions about the Forest Service role in aquatic invasive species research. In addition, Lindsay Chadderton (The Nature Conservancy), Steve Lindley (National Oceanic and Atmospheric Administration), Glen Contreras, Doug Ryan, Nick Schmal, Frank McCormick, Dede Olson, Mel Warren, Mike Young (Forest Service), and three anonymous reviewers provided helpful reviews of an earlier draft. Tami Lowry (Forest Service) formatted the document.

Literature Cited

Bisson, P.A.; Rieman, B.E.; Luce, C., et al. 2003. Fire and aquatic ecosystems of the Western USA: current knowledge and key questions. Forest Ecology and Management. 178(1–2): 213–229.

Brown, L.R.; Moyle, P.B. 1997. Invading species in the Eel River, California: successes, failures, and relationships with resident species. Environmental Biology of Fishes. 49: 271–291.

Fausch, K.D.; Rieman, R.E.; Young, M.K.; Dunham, J.B. 2006. Strategies for conserving native salmonid populations at risk from nonnative fish invasions: tradeoffs in using barriers to upstream movement. Gen. Tech. Rep. RMRS-GTR-174. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 44 p.

Great Lakes Regional Collaboration (GLRC). 2005. Great Lakes Regional Collaboration Strategy. http://www.glrc.us/strategy.html. (5 March 2007).

Harvey, B.C.; White, J.L.; Nakamoto, R.J. 2004. An emergent multiple predator effect may enhance biotic resistance in a stream fish assemblage. Ecology. 85: 127–133.

Kaller, M.D.; Kelso, W.E. 2006. Swine activity alters invertebrate and microbial communities in a Coastal Plain watershed. American Midland Naturalist. 156: 163–177.

Lee, D.C.; Sedell, J.R.; Rieman, B.E., et al. 1997. Broadscale assessment of aquatic species and habitats. In: Quigley, T.M.; Arbelbide, S.J., tech. eds. An assessment of ecosystem components in the interior Columbia basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-405 (Vol. 3). Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1057–1496.

Lodge, D.M.; Williams, S.; MacIsaac, H.J., et al. 2006. Biological invasions: recommendations for U.S. policy and management. Ecological Applications. 16: 2035–2054.

Ludwig, D.; Hilborn, R.; Walters, C. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science. 260: 17–36.

Master, L.L.; Stein, B.A.; Kutner, L.S.; Hammerson, G.A. 2000. Vanishing assets—conservation status of U.S. species. In: Stein, B.A.; Kutner, L.S.; Adams, J.S., eds. Precious heritage: the status of biodiversity in the United States. New York: Oxford University Press: 93–118.

National Invasive Species Council (NISC) and Aquatic Nuisance Species Task Force (ANSTF). 2007. Training and implementation guide for pathway definition, risk analysis and risk prioritization. http://www.anstaskforce.gov/Documents/Pathways_Training_and_Implementation_Guide_Jan_2007.pdf. (23 March).

National Research Council. 2004. Atlantic salmon in Maine. Washington, DC: National Academy Press. 304 p.

Nislow, K.H.; Magilligan, F.J.; Fassnacht, H., et al. 2002. Effects of hydrologic alteration on flood regime of natural floodplain communities in the Upper Connecticut River. Journal of the American Water Resources Association. 38(6): 1533–1548.

Raffia, K.F.; Bonello, P.; Cameron, R.S., et al. 2006. USDA Forest Service invasive species research and development panel. Report submitted to the Forest Service, Washington, DC. 16 p.

Ricciardi, A. 2006. Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity. Diversity and Distributions. 12: 425–433.

Richardson, D.M.; Holmes, P.M.; Else, K.J., et al. 2007. Riparian vegetation: degradation, alien plant invasions, and restoration prospects. Diversity and Distributions. 13: 126–139.

Rinne, J.N. 1996. The effects of introduced fishes on native fishes: Arizona, Southwestern United States. In: Philipp, D.P., ed. Protection of aquatic diversity: proceedings of the First World Fisheries Congress. New Deli, India: Oxford & IBH Publishing: 149–159.

Rinne, J.N.; Medina A.L. 1996. Implications of multiple use management strategies on native southwestern (USA) fishes. In: Meyer, R.M., ed. Fisheries resource utilization and policy: proceedings of the First World Fisheries Congress. New Deli, India: Oxford & IBH Publishing: 110–123.

Singer, F.J.; Swank, W.T.; Clebsch, E.E.C. 1984. Effects of wild pig *Sus scrofa* rooting in a deciduous forest. Journal of Wildlife Management. 48: 464–473.

U.S. Department of Agriculture, Forest Service. 1995. Forest service manual, title 2600, wildlife, fish and sensitive plant habitat management, amendment no. 2600-95-7, section 2670.22. Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Federal Aquatic Nuisance Species Task Force (USFANSTF). [N.d.] ANS task force. http://www.anstaskforce.gov. (28 March 2007).

U.S. Geological Survey (USGS). 2008. NAS—nonindigenous aquatic species. http://nas.er.usgs.gov/queries/default.asp. (7 August 2000).

Wilcove, D.S.; Rothstein, D.; Dubow, J., et al. 2000. Leading threats to biodiversity: what's imperiling U.S. species? In: Stein, B.A.; Kutner, L.S.; Adams, J.S., eds. Precious heritage: the status of biodiversity in the United States. New York: Oxford University Press: 239–254.