Effects of Nonindigenous Invasive Species on Water Quality and Quantity

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Abstract

Physical and biological disruptions of aquatic systems caused by invasive species alter water quantity and water quality. Recent evidence suggests that water is a vector for the spread of Sudden Oak Death disease and Port-Orford-cedar root disease. Since the 1990s, the public has become increasingly aware of the presence of invasive species in the Nation's waters. Media reports about Asian carp, zebra mussels (*Dreissena polymorpha*), golden algae (*Prynmesium parvum*), cyanobacteria (*Anabaena* sp., *Aphanizomenon* sp., and *Microcystis* sp.), and New Zealand mud snail have raised public awareness about the economic and ecological costs of invasive species. Along with other Federal agencies, States, and communities, Forest Service R&D must work to fund the research needed to better understand the linkages of land and water as venues for ecosystem effects of invasive species biology. This paper will identify desired resource outcomes, address management strategies and systems needed to achieve the outcomes, discuss potential effects on riparian systems and water resources, and identify research and actions needed to achieve the desired outcomes.

Introduction

In 1993, the Office of Technology Assessment (OTA), a former office of the U.S. Congress, estimated that 10 percent of all nonindigenous species posed a threat to become a nuisance species. According to the U.S. Environmental Protection Agency (EPA), more than one-third of all States have waters that are listed for invasive species under section 303d of the Clean Water Act of 1977. Nonindigenous species cause ecological damage, human health risks, or economic losses. Invasive species are degrading a suite of ecosystem services that the national forests and grasslands provide, including recreational fishing, boating, and swimming; municipal, industrial, and agricultural water supply; and forest products. Degradation of these services results in direct economic losses, costs to replace the services, and control costs. Losses, damages, and control costs are estimated to exceed $178 billion annually (Daily et al. 2000a, 2000b). Although agriculture is the segment of the economy most affected ($71 billion per year), costs to other segments, such as tourism, fisheries, and water supply, total $67 billion per year. Although more difficult to quantify, losses of these ecosystem functions also reduce the quality of life. Such costs are not assessed as losses to ecosystem services.

A review of studies on the economic effect of invasive species in the United States found that most are of limited use for guiding decisionmakers who formulate Federal policies on prevention and control (GAO 2002). They focused narrowly on estimates of past damages to a few commercial activities, agricultural crop production, and accountings of the money spent to combat a particular invasive species. These estimates typically do not examine economic damage done to natural ecosystems, the expected costs and benefits of alternative control measures, or the possible effect on future invasions by other species. Initiatives by Federal agencies to integrate information on the likelihood of invasion, the likelihood of economic damage to commercial activities and natural ecosystems, and the likely effectiveness of control methods are hampered by a lack of necessary data and of targeted resources.

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The Forest Service has a major role in the management of invasive species. Forest Service Research and Development (R&D) has unique capabilities to address the complex interactions among natural processes, land use, water resources, and invasive species and to meet future challenges through collaboration across mixed ownership and agencies. The Forest Service plays a vital role in managing 192 million acres of 156 national forests and grasslands, including 2 million acres of lakes, ponds, and reservoirs; more than 200,000 miles of perennial streams; and more than 16,500 miles of coastline. The Forest Service also provides technical assistance for 731 million acres of forests, rangelands, and prairies managed by other Federal agencies, States, private owners, and tribes. The Forest Service faces future challenges to reduce the introduction and spread of aquatic and riparian invaders while helping to protect one of the Nation's most critical resources—drinking water. National forests and grasslands are the source of drinking water for 3,400 cities and towns, serving an aggregate population of more than 60 million people. More than 3,000 non-community water supplies, such as campgrounds, are also on National Forest System (NFS) lands. Public lands managed by the Forest Service and its cooperating agencies play a dominant role in the Western United States. Roughly 75 percent of all water originates on NFS lands, giving the Forest Service the primary influence on water resources. Water issues increasingly dominate the agency's interests, and understanding the major direct and indirect effects of invasive species on water quality, water availability, and aquatic biological integrity will be increasingly important to the Forest Service mission and strategic goals. Amid growing public and political concern, we may anticipate growing pressure from a suite of stakeholder groups demanding that the Forest Service take a more active role in researching and managing aquatic invasive species. These pressures will be complicated by opposing stakeholder values regarding control measures (e.g., use of pesticides and piscicides) and regarding the relative benefits or harm of particular exotic species (e.g., exotic fish and plants in Western streams).

Authorities

The Organic Administration Act of 1897, the Multiple-Use Sustained-Yield Act of 1960, and the National Forest Management Act of 1976 authorize the Forest Service to establish and administer national forests to secure the sustainable benefits of multiple uses for the American people. The Clean Water Act mandates that Federal agencies "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" and 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." The National Environmental Policy Act (NEPA) of 1969, Nonindigenous Aquatic Nuisance Species Prevention and Control Act of 1990, Lacey Act of 1900, and Endangered Species Act of 1973 authorize Federal agencies to prevent the introduction of invasive species; provide for their control; and take measures to minimize economic, ecological, and human health effects, including the effects of pesticides and biocontrol agents.

Building on these and other statutes, Executive Order 13112 (February 3, 1999; http://www.invasivespecies.gov) calls for Federal agencies to use relevant programs and authorities to:

1. Prevent the introduction of invasive species.
2. Detect and respond rapidly to, and control populations of, such species in a cost-effective and environmentally sound manner.
3. Monitor invasive species populations accurately and reliably.
4. Provide for restoration of native species and habitat conditions in ecosystems that have been invaded.
5. Conduct research on invasive species and develop technologies to prevent introduction and provide for environmentally sound control of invasive species.
6. Promote public education on invasive species and the means to address them.

In addition, Order 13112 states that Federal agencies shall "not authorize, fund, or carry out actions that it believes are likely to cause or promote the introduction or spread of invasive species."

The National Aquatic Invasive Species Act now before Congress would reauthorize and strengthen the National Invasive Species Act of 1996 to protect U.S. waters by preventing new introductions of aquatic invasive species. The legislation, which Senator Carl Levin, D-Michigan, is sponsoring along with Senator Susan Collins, R-Maine, would regulate ballast discharge from commercial vessels; prevent invasive species introductions from other pathways; support State management plans; screen live aquatic organisms entering the United States for the first time in trade; authorize rapid response funds; create education and outreach programs; conduct research on invasion pathways, and develop prevention and control technologies for those pathways; authorize funds for State and regional grants; and strengthen specific prevention efforts in the Great Lakes.

Research Needs Regarding Invasive Species Effects on Water Quality and Quantity

Forest Service R&D is providing research and science delivery leadership to integrate diverse objectives associated with the management and conservation of aquatic resources under threat from invasive species. To focus its research, Forest Service R&D needs to work with the NFS to identify the highest priority needs. Besides targeted invasive species research, much of the ongoing ecological research could incorporate invasive species as a stressor at little additional cost. Adams, et al. (this volume) discussed Forest Service R&D roles specific to aquatic invasive species research. This chapter focuses on the impacts of invasive species on water quality and quantity.

Key questions include:

1. What will we require our riparian systems and water resources to produce in the coming decades?
2. What are the major goods, services, and values that may be disrupted by invasive species?
3. How will invasive species affect water resources and what are the associated socioeconomic effects?
4. What are our future management, policy, and societal needs to mitigate or adapt to the effects of invasive species as they alter the ability of aquatic ecosystems to provide these goods, services, and values?
5. How can research provide management systems and strategies for interactions between invasive species and water resources to optimize continued future production of these goods and services?
6. What are the effects on native species biodiversity, and the noneconomic societal values for maintaining that biodiversity?

Water quality and quantity are affected by the plants and animals that live in or near aquatic environments, as well as by management actions taken to control these taxa. For example, stocked fish are capable of hybridizing with closely related native species (Fausch et al. 2006). Introduced hatchery rainbow trout hybridized with Alvord Redband Trout, resulting in its becoming extinct in the wild. The Red Shiner (C*yprinella lutrensis*) is a highly competitive, aggressive invasive species that has been widely introduced in rivers and streams in the United States by bait bucket transfer and stocking as a forage fish (Nico and Fuller 2007; USDA Forest Service 2004). It is implicated in the decline of native fish through hybridization, competition, and the introduction of pathogens (Walters, et al. 2008; Deacon 1988; Holden and Stalnaker 1975; Mettee et al. 1996). Introduction of fish in aquatic systems can affect trophic relationships and set off "trophic cascades" with resulting declines in native species and degradation of water quality (Baxter et al. 2004; Eilers et al. 2007).

Whirling disease was first introduced to the United States from Europe in the early 1900s through infected brown trout that were brought to Pennsylvania. The highly infectious disease has gradually moved to lakes and streams in Western States. The disease can be spread by fish, people, dogs, birds, boat trailers, hip boots, and fishing equipment that have been in infected waters. After entering a water body, the virus persists through spores that can survive for up to 30 years, even in dried-up streambeds. In response to the spread of the disease, Colorado implemented a complicated and costly ($12M) management and remediation program that prevents the stocking of trout from hatcheries testing positive into waters where whirling disease has not been found. This prohibition includes wilderness areas and streams where native trout may be restored. Trout from positive hatcheries will be only stocked into waters where the parasite has already been found to minimize the risk of contaminating other watersheds; however, stocking infected fish only perpetuates the problem.

Research on the effects of fish stocking in native ecosystems may require incorporation of economic analyses of the tradeoffs between conservation of native species and reduced recreational enjoyment. This analysis would be especially complex in the Western United States where native and introduced species have both commercial and recreational value. Matthews et al. (2001) and Knapp (2005) reported reductions in native amphibian populations in montane lakes in the Sierra Nevada Mountains of California where trout had been stocked. Dunham et al. (2004) identified multiple negative associations of native species with introductions of nonnative trout in the Western United States. Arresting human-mediated transport of invasive species will require support for public education programs such as Stop Aquatic Hitchhikers (a partnership among several Federal and State agencies, private industry, and nongovernmental organizations). Such programs may be effective at reducing the inadvertent transport of aquatic invasive species and pathogens between water bodies, but they must be able to identify specific potential threats.

Because of accelerating invasion rates, widespread economic costs, and environmental damages caused by invasive species, colonization theory has lately become a matter of considerable interest to aquatic ecologists. A synthesis of models of population growth, invasion biology, and theoretical population biology might provide quantitative tools for risk assessment of biological invasions. Retrospective and predictive models derived from rangewide analyses of potential invasive species of concern could be used to map historic and current localities of species nationally and to conduct analyses of patterns of dispersal and future threats. In the face of climate change and shifting human populations, the most vulnerable water resources could be identified and neighboring population centers targeted for public education campaigns that would reduce the potential for recreational users to spread invasive species through inadvertent or intentional introductions.

The identification and risk assessment of potential biological invaders would provide valuable criteria for the allocation of resources toward the detection and control of invasion threats (Anderson et al. 2004; Orr 2003). Ricciardi and Rasmussen (1998) identified 17 species from the Black, Caspian, and Azov seas (the origins of the zebra and quagga mussels (*Dreissena* spp.) and round goby (*Neogobius melanostomus*)) that could invade the Great Lakes-St. Lawrence River system and other North American inland waterways via the same vectors as previous invasive species. Characterizing life history traits of invaders may require increased international collaboration to identify limiting factors in the native range of the alien species. Whittier et al. (2008) developed a calcium-based invasion risk assessment for zebra and quagga mussels (*Dreissena* spp.) for streams in the Western United States.

Monitoring and assessment need to be conducted at appropriate scales to identify associations between native and invasive species. This approach will also affect the ability to detect direct or indirect species interactions. Brown and Moyle (1997) suggest that the success or failure of introductions of stream species are a function of the ability of a species to survive the fluctuating, highly seasonal, flow regime. Vaughn and Spooner (2006) emphasize the importance of appropriate sample scale in examining potential associations between species. One reason for underlying disparate conclusions about the ability of native and invasive species to coexist may be the different spatial scales at which data have been collected. Studies of the effects of nonindigenous species on aquatic food webs may require retrospective studies of population abundance to identify the responses of native species to the arrival of an invasive species (Laxson et al. 2003). It is also important to improve our understanding of spatial patterns associated with invasions of nonindigenous species from patch to landscape scales.

Early detection and monitoring of invasive species require that the methods for species collection and identification are rapidly deployable, cost effective, applicable across a range of ecosystems, and capable of identification of multiple taxa. Traditionally, these approaches are based on morphology. Mass identification of multiple taxa, especially for diverse micro- and meio-faunal groups is time consuming, technically intensive, and costly. An emerging methodology for early detection and monitoring of invasive species is the use of "environmental DNA" or e-DNA (Darling and Blum 2007). This "DNA barcoding" or "community metagenomics" (Tringe and Rubin 2005) based on the limited persistence of DNA in the environment has been used to detect the presence of an invasive species in freshwater systems (Ficetola et al. 2008).

Scientists have demonstrated that the introduction of fish and other species into previously fishless systems has caused major changes in abundance and distribution of native amphibians, zooplankton, and benthic invertebrates, particularly in high mountain lakes. Scientists will need to continue to evaluate the effects of introduced fishes on invertebrates, amphibians, reptiles, birds, and bats. A topic area of interest is high mountain lakes where introductions of trout for recreational sportfishing have caused declines in native amphibian populations. Where climate change is affecting temperature regimes, increasing temperatures may favor the spread of invasive species or pathogens or increase competition among juvenile salmon for temperature refugia. Management activities that could reduce the water temperature to historic thermal regimes could reduce the effect of invasive species on native salmonids.

Insect and disease outbreaks often lead to increased harvesting of the host species, including preemptive cutting before the arrival of the damaging organism as well as post-mortality salvage logging. Although such harvesting is seldom included as an indirect effect of the outbreak, it often includes removal of non-host species and may generate more profound ecosystem disruption than the pest or pathogen itself (Foster and Orwig, 2006). Studies comparing changes in microenvironment, vegetation, and ecosystem processes initiated by infestation by HWA, salvage logging, and preemptive logging of hemlock indicate that logging initiated stronger ecosystem changes than HWA-induced mortality due to abrupt and larger micro-environmental and vegetation changes, soil scarification, and the presence of extensive slash. Dramatic alterations in nitrogen cycling followed harvesting and persisted for many years.

Consequently, preemptive cutting appears to pose the greatest threat for nitrate leaching, followed by logging of declining sites and then by decline in the absence of logging (Foster and Orwig, 2006). Compositional changes between harvested and infested stands were similar overall but occurred at very different temporal and spatial scales. Following logging, there was a much greater increase in shade-intolerant seedlings, saplings, and herb layers (Kizlinski et al. 2002). It is important to evaluate such effects more broadly to help land managers make informed decisions about the best response to invasive species and natural disturbances.

New assessment and monitoring tools are needed to help manage the diversity of aquatic species necessary for successful land management projects that will conserve and recover species at risk. Baseline scientific information collected before large catastrophic events helps set priorities and assists with resource restoration after events such as hurricanes and large-scale wildfires. For example, using fish and fish habitat surveys to map changes in species occurrences and abundances over time, managers can evaluate the effects of management treatments for invasive species on native and nonindigenous aquatic species. The information could be used to assess watershed condition and aquatic biodiversity for uses such as forest plan revisions, forest project planning, NEPA evaluations, management indicator species status reports, populating the Natural Resource Information System database, State and sensitive forest species evaluations, analysis of potential effects to aquatic diversity of reservoir placement, and a year-long analysis of fish recovery from severe drought.

Scientists recognize that riparian communities are among the most susceptible to invasion by nonnative species. Nationwide, in many streams and rivers, the native plants and animals were adapted to a system of dynamic equilibrium that included flood disturbance and wildfire to maintain diverse structure, age class, and community composition. Today, dams, diversions, ground water extraction, channelization, grazing, roads, and recreational use have modified many of these streams and watersheds to create conditions that favor some of the most aggressive invasive species. Riparian forests support the highest density and diversity of breeding birds in the Desert Southwest. These forests were historically shaped by regular flood events that were instrumental in the recruitment of native vegetation. Native riparian vegetation provides numerous nesting sites for a variety of Southwestern birds and also supports specialized arthropods, such as cicada, which are an important part of birds' diets during the breeding season. Current research includes measuring vegetation and changes in structure and recovery of native and exotic vegetation at study sites and sampling arthropods, bird populations, and nesting success. Using this research, models can then be developed to propose management strategies aimed at mitigating the effects of altered disturbance regimes on riparian vegetation structure, arthropod abundance, and habitat utilization and nesting success.

The balsam wooly adelgid (*Adelges piceae*) has killed virtually all the adult firs in Great Smoky Mountains National Park, thereby eliminating almost three-fourths of the spruce-fir forests in the Southern United States. As this dominant canopy tree disappears, the forests become warmer and drier. The subsequent change in temperature jeopardizes the survival of several northern species that have persisted as Ice Age relicts in these cool, high-elevation Appalachian forests. Studies have documented that spatial patterns of insect damage were more severe along the stream courses and less severe away from the streams (Kimpel and Schuster 2002). Stand productivity and water use appear little affected until an intermediate threshold of damage has occurred. Enhanced soil moisture availability may first be noticed toward the end of the growing season. After trees reach heavily damaged status, water uptake and transpiration are severely reduced throughout the growing season, leaving substantially more water available for evaporation, runoff, and/or use by other plant species. HWA also exhibits clear spatial patterns of damage as it spreads through hemlock stands. Moderate to heavy damage is common 4 to 8 years after initial colonization. The greatest damage is found at presumed initial contact areas, but this pattern appears to fade over time. Managers can expect that mortality will first occur in these areas and that they may have more time to implement control strategies in more interior locations. Thus, managers can expect that both productivity and water use may be little affected until an intermediate threshold of damage has occurred.

Future Considerations

Although most studies of the effects of invasive species relate to direct effects on native species, indirect, synergistic, or cumulative effects on aquatic systems are less well understood. To manage the disturbance caused by invasive species, land management agencies will need to rely on interdisciplinary research that involves the skills of aquatic biologists, hydrologists, silviculturists, soil scientists, biogeochemists, pathologists, and others. Forest Service R&D can avail itself of core strengths in long-term research on its experimental forests and rangelands. Research can provide landscape-scale modeling to support early detection, risk assessment, and mitigation of the effects of management activities to reduce or eradicate invasive species. Improving survey and inventory monitoring designs to maximize the likelihood of early detection of invasive species based on predictive models of the intrinsic potential of stream corridors, lakes, and wetlands to harbor invasive species may help ensure that invaders do not gain a foothold in previously unaffected areas.

Invasive species affect the quantity and timing of runoff, erosion, sedimentation, and other natural physical processes and may affect water availability in general. The hydrologic effects of invasive riparian species, such as salt cedar (*Tamarix* spp.), which consumes 10 to 20 times the water used by native species, may lower the water table and dry stream reaches in some areas (Wiesenborn 1996). In other cases, invasive species may lead to increased susceptibility to flooding. Stands heavily damaged by HWA may experience increased soil moisture due to reduced transpiration and may deliver increased runoff to headwater streams.

Various means exist for nonindigenous species to degrade water quality. Decreased flows reduce transport of nutrients. Increased runoff and erosion increase sedimentation or alter nutrient flux. Replacement of bunchgrass by knapweed has increased erosion, raising stream temperatures and reducing fish habitat (Lacey et al. 1989). Cheatgrass in the arid West shades out nitrogen-fixing soil crusts, decreasing nitrogen input to the ecosystem (Whisenant 1990). Decomposition of invasive plants, such as Eurasian water millfoil, alters the loading cycles of nitrogen and phosphorus. Following dieoff, bacterial decomposition of decaying plant material can reduce dissolved oxygen. Zebra mussels (*Dreissena polymorpha*) filter particles from the water column and concentrate nutrients in their feces, changing nutrient regime and enriching sediment. They also change water clarity and alter conditions for native species adapted to turbidity, were shown to accumulate and transfer water-borne contaminants to other benthic invertebrates (Bruner et al. 1994; Hart, et al. 2001), and contributed to a bloom of cyanobacteria in the Great Lakes (Vanderploeg et al. 2001). New Zealand mud snails composed such a major portion of the biomass in a Wyoming mountain stream that they consumed 75 percent of gross primary productivity, and their excretions accounted for two-thirds of ammonium demand (Hall et al. 2003). Tui chub were introduced in Diamond Lake, OR, in the 1950s as a forage fish. Tui chub eat microscopic zooplankton that would normally graze on phytoplankton in the lake. The decreased zooplankton population resulted in uncontrolled growth of several forms of algae, including the blue-green algae (*Anabaena* sp.), which released the toxin anatoxin-a into the water (Tanner et al. 2005). The effect of Tui chub is now more than the loss of fishing opportunity. It is affecting water quality and overall recreation use and is causing serious public health concerns (Eilers et al. 2007). Multiple efforts to eradicate the Tui Chub have failed to eliminate the species from the system.

Terrestrial and aquatic invasive species can dramatically alter the loadings of nutrients, clean sediments, and toxic pollutants into surface and estuarine waters. Invasive aquatic species, such as the zebra mussel, can alter the toxic effects and bioaccumulation of contaminants by altering pollutant fate and dynamics within water bodies (Endicott et al. 1998). Zebra mussels remove contaminant-bearing particles from the water column and deposit them in sediments. Contaminants become available to benthic invertebrates and enter the food web (Bruner et al. 1994). Among the more significant indirect effects is the increased pesticide exposure in the environment due to eradication efforts. The majority of pesticides is targeted for controlling exotic weeds, insects, and mites (Lee and Chapman 2001; Pimentel et al. 1992). As new exotic pests are introduced, the use of pesticides targeted for their control will increase with a commensurate increase in ecological and human health effects. In addition, by altering erosion, runoff, and deposition processes, terrestrial, wetland, and aquatic invasive species can substantially alter pollutant loadings into surface and estuarine waters.

The spread of exotic diseases such as West Nile Virus by water are related to the breakdown of the same ecological, social and economic barriers associated with the introduction of other nonindigenous species. Emerging infectious diseases are a key threat to conservation and public health, yet predicting and preventing their emergence is notoriously difficult. Recent evidence suggests that water is a vector for the spread of Sudden Oak Death disease and Port-Orford-cedar root disease. This finding poses a significant challenge for the future. Management options for these two water molds, including chlorination of firefighting water, are costly and are accompanied by their own environmental effects. Introductions of nonindigenous amphibians such as the bullfrog (*Rana catesbeiana*) may contribute to the spread of the chytrid fungus (http://www.werc.usgs.gov/fs/amphstat.pdf) that has been linked to severe population declines in native amphibians. Several of these exotic diseases have the potential to become serious regional or national public health threats, and their number and geographical extent are likely to increase with global climate change. To understand the cascade of ecosystem effects, research needs to identify the fundamental processes that prevail in undisturbed systems before we can evaluate detect the direct and indirect responses of those systems affected by invasive species.

Managers developing response plans to aquatic ecosystem disturbances need to understand the synergies and cumulative effects as well as the socioeconomic impacts in order to resolve conflicting values surrounding recreation or restoration activities, such as Burned Area Emergency Response restoration priorities, stream restoration, or fish stocking (Fausch et al. 2006).

Other research needs include:

- Develop genetics-based methods for early detection of invasive aquatic and terrestrial species by identifying likely invaders and susceptible habitats.
- Conduct research on geographic variation of invasive species to increase the understanding of the spread of these species after they are established.
- Determine invasive species effects across trophic levels (interactions of invasive plants and animals) in selected landscapes such as Hawaii, other Pacific Islands, and the Caribbean.
- Determine distribution and habitat relationships of introduced species in managed aquatic and terrestrial systems, and develop a risk analysis to determine priority species for research.
- Develop experimental approaches to investigating ecosystem responses to invasive removal in priority land types, such as wilderness.
- Develop methods for rapid detection and efficient monitoring of invasive species in large river systems or at large geographic scales.
- Determine whether salvage logging in riparian areas reduces the spread of invasive species, and what management options are available.
- Develop instructional materials for training field crews in the proper methods to decontaminate field equipment to prevent the spread of aquatic invasive species and pathogens.

Conclusions

According to the EPA, more than one-third of all the States have waters that are listed for invasive species under section 303d of the Clean Water Act. All waters currently listed as impaired by nonindigenous species have been determined by a case-by-case analysis. It is not clear if the Forest Service will ultimately consider invasive species such as noxious aquatic plants as pollutants for Clean Water Act purposes. To the extent that terrestrial and aquatic nonindigenous species affect watershed condition by altering erosion, runoff, and deposition processes, failure to account for these effects in total maximum daily load models could result in substantial errors in calculating load allocations.

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