U.S. Geological Survey Invasive Species Research—

Improving Detection, Awareness, Decision Support, and Control

Circular 1485

U.S. Department of the Interior
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Cover. An invasive red lionfish waits to be brought to the surface, where it will eventually be used by the National Oceanic and Atmospheric Administration in lab studies on reproductive biology, age, and growth of lionfish. Photograph by Karen Doody, U.S. Geological Survey.

Title page. Invasive cheatgrass turning red in the fall in the Squirrel Creek burn area, Medicine Bow National Forest, Wyoming. Photograph by the U.S. Geological Survey.

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Paddling across Kintla Lake in Glacier National Park, Montana, to a site to sample for invasive lake trout which negatively affect native bull trout. Photograph by Michael Meeuwig, U.S. Geological Survey.

A 16 1/2-foot Burmese python that was captured in a thicket in Everglades National Park in Florida is removed from the wild by staff from the National Park Service and the U.S. Geological Survey. Photograph by Catherine Puckett, U.S. Geological Survey.

U.S. Geological Survey Invasive Species Research—Improving Detection, Awareness, Decision Support, and Control

By Cindy Kolar Tam,[1] Wesley M. Daniel,[1] Earl Campbell,[2] James J. English[1], and Suzanna C. Soileau[1]

More than 6,500 nonindigenous species are now established in the United States, posing risks to human and wildlife health, native plants and animals, and our valued ecosystems (Simpson and Eyler, 2018). The annual environmental, economic, and health-related costs of invasive species are substantial. Invasive species can drive native species onto the endangered species list, resulting in associated regulatory costs; exacerbate the threat of wildland fire, which destroys property and threatens lives; increase the cost of delivering water and power; damage infrastructure; and degrade recreation opportunities and discourage tourism (U.S. Department of the Interior, 2021). The U.S. Geological Survey (USGS) works with sister agencies in the U.S. Department of the Interior (DOI) and other Federal, State, and territorial agencies, Tribes, and other stakeholders to provide information and tools needed to help solve problems posed by invasive species across the country. Key components of USGS invasive species science include developing novel prevention, forecasting, early detection, decision support, and control tools (fig. 1).

[1]U.S. Geological Survey.

[2]U.S. Fish and Wildlife Service.

Invasive Species Facts

- For the purposes of this report, invasive species are defined as a nonindigenous species whose introduction outside their native range causes harm to the environment, infrastructure, economy, or human health.
- Invasive species adversely affect every State, territory, and Tribe in the Nation and every habitat type, from those in urban centers to wilderness areas; in 2005, the annual cost to the U.S. economy was estimated to be more than $120 billion (Pimentel and others, 2005).
- Invasive species compete with and prey on native plants and wildlife, impair critical water infrastructure, transmit disease to wildlife and humans, threaten commercial and native fisheries, decrease agricultural production, and reduce hunting, fishing, and other recreational opportunities, including boating and swimming.

Eelgrass (*Zostera* spp.) in Hogum Bay, Washington. Photograph by Sierra Blakely, U.S. Geological Survey.

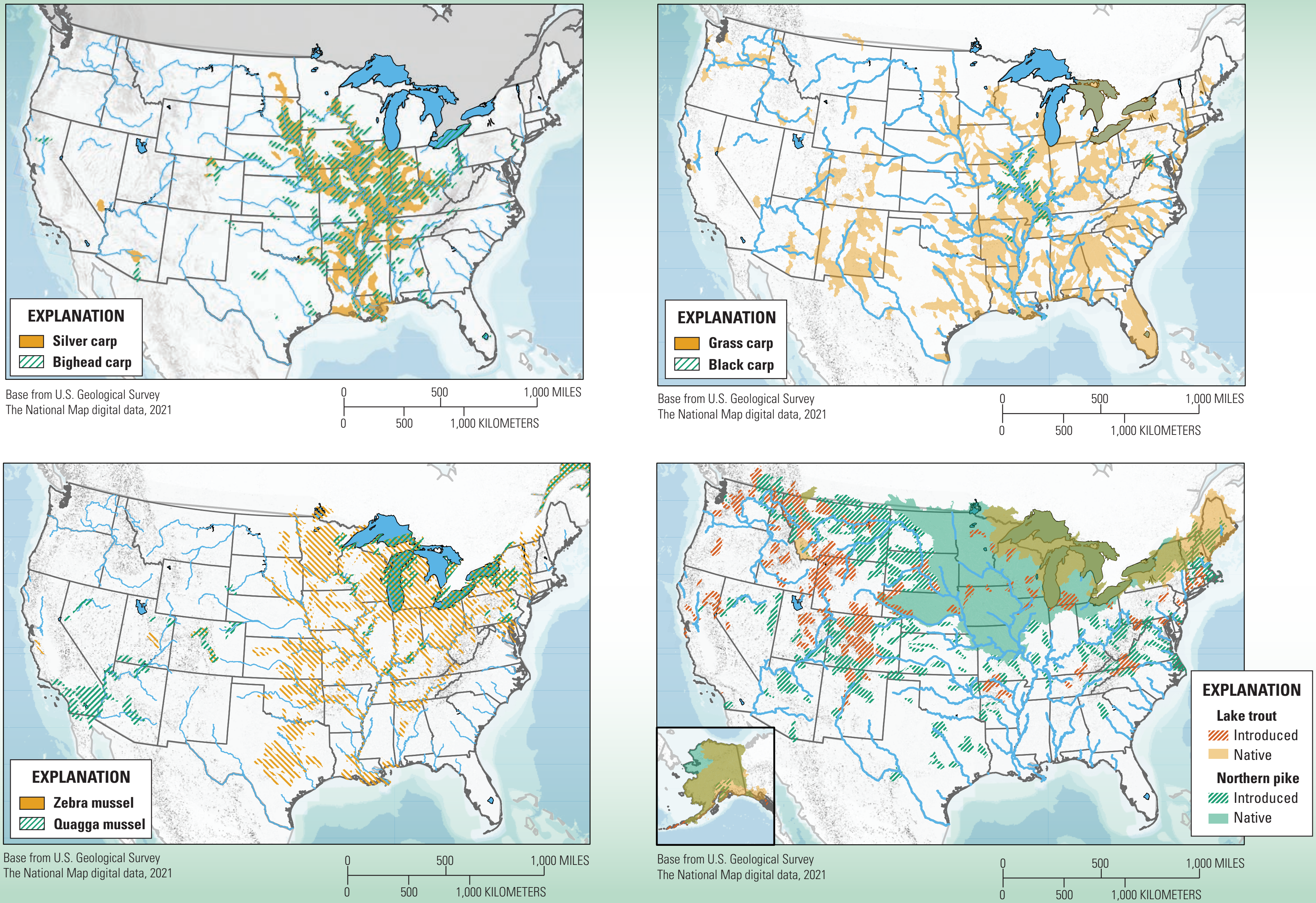


Figure 1. Areas of emphasis for invasive species research at the U.S. Geological Survey.

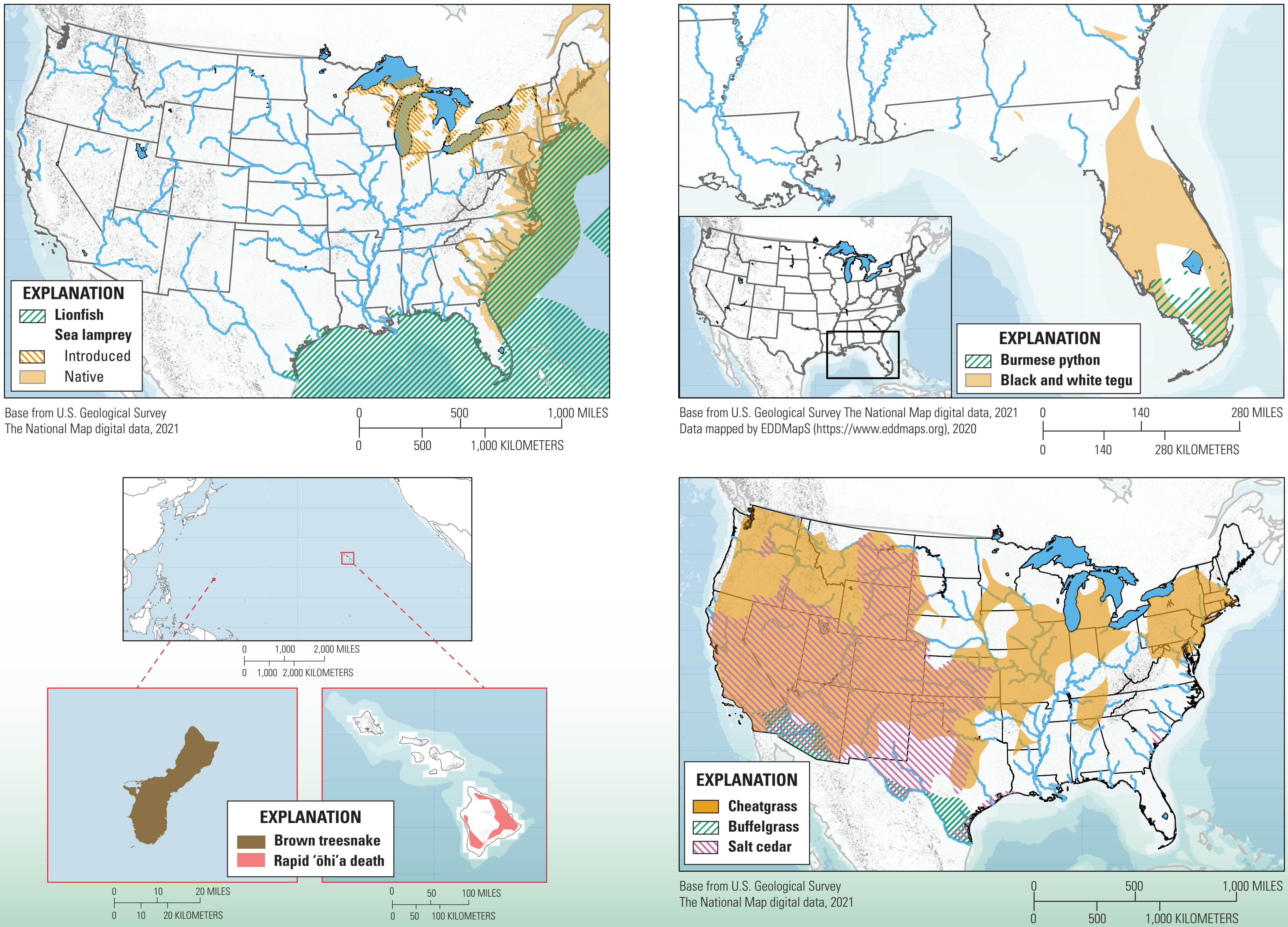


Figure 1. Areas of emphasis for invasive species research at the U.S. Geological Survey.—Continued

The USGS is developing a nationwide biosurveillance network to support DOI goals related to detecting invasive species (fig. 1), which include the following:

- Provide situational awareness of invasive species by mapping the spread; forecasting potential arrival, extent, and effects; and synthesizing information into decision-making frameworks and public databases.
- Provide nationwide reporting, monitoring, and tracking of all freshwater aquatic invasive species as part of a national early detection system.
- Prevent establishment and further spread of invasive carps (bighead carp [*Hypophthalmichthys nobilis*], black carp [*Mylopharyngodon piceus*], grass carp [*Ctenopharyngodon idella*], and silver carp [*H. molitrix*]) in the Great Lakes, Upper Mississippi, and other subbasins of the Mississippi River through the development of state-of-the-art detection and control tools.
- Assist Federal, State, and Tribal partners with detection, mapping, and control support to manage zebra (*Dreissena polymorpha*) and quagga (*D. bugensis*) mussels in the continental United States.
- Develop innovative detection tools for many invasive species, including rapid ´ōhi´a death in Hawaii. Rapid ´ōhi´a death is a disease caused by the fungi *Ceratocystis lukuohia* and *C. huliohia* that attack and kill ´ōhi´a lehua (*Metrosideros polymorpha*) trees on the Island of Hawai´i within days or weeks by clogging the tree's vascular system, depriving it of water.
- Support management efforts related to invasive plants, such as salt cedar (*Tamarix* spp.), cheatgrass (*Bromus tectorum*), Russian olive (*Elaeagnus angustifolia*), Siberian elm (*Ulmus pumila*), leafy spurge (*Euphorbia esula*), brome (*Bromus* spp.), reed canary grass (*Phalaris arundinacea*), buffelgrass (*Cenchrus ciliaris*; synonym, *Pennisetum ciliare*), Brazilian waterweed (*Egeria densa*), phragmites (*Phragmites australis*), and melaleuca (*Melaleuca quinquenervia*).
- Support control of brown treesnake (*Boiga irregularis*) on Guam, sea lamprey (*Petromyzon marinus*) in the Great Lakes, and Burmese python (*Python bivittatus*) and black and white tegu (*Tupinambis merianae*) in southern Florida by developing and deploying monitoring, mapping, and control techniques.

Startled by the sound of a motorboat, silver carp in the Illinois River, Illinois, jump in the wake of the boat. Photograph courtesy of the U.S. Fish and Wildlife Service.

Biosurveillance Network for Invasive Species and Wildlife Disease

Across the Nation, the risks caused by biological threats, such as invasive species and wildlife disease-causing organisms, are increasing, costing the U.S. economy, as estimated in 2005, more than $120 billion annually (Pimentel and others, 2005) and directly affecting the health of humans, wildlife, and domestic animals. In recent years, from 2010 to 2017, global biological invasions cost $29.2 billion annually (Diagne and others, 2021). Being able to quickly detect, characterize, and respond to biological threats is paramount to national security and protecting food and water supplies. The USGS is a trusted resource for Federal, State, local, and Tribal natural resource managers to help identify and assess risks associated with biological threats. In cooperation with the U.S. Fish and Wildlife Service (FWS), the USGS has established a nationwide network for biosurveillance of invasive species and wildlife disease.

The nationwide capabilities of the USGS in prevention, prediction, early detection, containment, and control of invasive species and wildlife disease through an effective biosurveillance network add value to ongoing efforts to protect the health and safety of the Nation. USGS field expertise, tools, techniques, and technologies, including molecular methods, help develop and enhance early detection biosurveillance capacities. Efforts of the nationwide biosurveillance network address ongoing and emerging needs through research projects that improve biological threat detection, interagency communication, and early detection and rapid response decision making. The USGS is developing a steering committee with representatives from other DOI agencies to help guide the implementation and priorities of the network. In addition, the DOI invasive species strategic plan recognizes the value of the USGS building this biosurveillance network to aid in early detection and rapid response efforts.

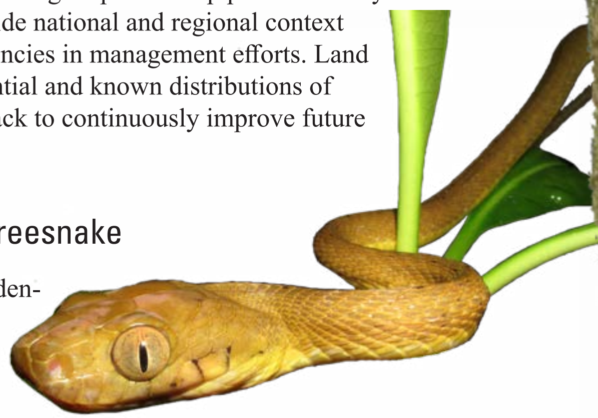
Extensive mortality of invasive tamarisk following biological control on the Virgin River, Nevada. Photograph by Patrick B. Shafroth, U.S. Geological Survey.

Early Detection and Rapid Response Tool Development

Early detection and rapid response refers to a coordinated set of actions to detect and eradicate potential invasive species before it spreads, becomes established, and causes harm. The USGS is developing a number of science products to support resource managers in implementing early detection and rapid response.

Mapping Tools

USGS scientists are developing mapping tools for predicting the potential invasion and distribution of invasive species identified as a priority by the DOI, such as invasive carps and mussels. The resulting maps can help prioritize early detection and rapid response efforts and provide national and regional context to local invasions, increasing efficiencies in management efforts. Land managers will be able to view potential and known distributions of invasive species and provide feedback to continuously improve future mapping products.



Rapid Response to Brown Treesnake

The brown treesnake was accidentally introduced to Guam in the late 1940s and has caused significant ecological and economic damage (Fritts and Leasman-Tanner, 2001). Established in 2002, the multiagency Brown Treesnake Rapid Response Team (U.S. Geological Survey, 2021c), led by the USGS, was created to ensure effective early detection and rapid response efforts for sightings of brown treesnake in new locations on the Pacific Islands, such as the Northern Mariana Islands. The Brown Treesnake Rapid Response Team leads training courses and manages multiagency responses to brown treesnake sightings. Training courses include extensive visual searching to develop the ability to find and capture snakes, as well as instruction on the use of snake traps and proper interview techniques when gathering observation data from the public. The USGS has developed a model for determining the amount of visual searching and trap effort required when responding to brown treesnake rapid response efforts to meet the desired degree of certainty by resource managers that a population is not present in the area. The work of the USGS on brown treesnake serves as a model on how to interdict and respond to other invasive species deemed a priority.

Closeup of an invasive brown treesnake. Photograph by Bjorn Lardner, U.S. Geological Survey.

Nonindigenous Aquatic Species Database

The nonindigenous aquatic species database (U.S. Geological Survey, 2021n) was developed by the USGS in 1990 to be a central repository for sightings of invasive and nonindigenous aquatic plant and animal species throughout the United States and its territories, including for more than 1,330 freshwater and marine species (fishes, crustaceans, mollusks, mammals, reptiles, amphibians, and plants). The confirmed species sightings are made available for use by Federal, State, and Tribal agencies, interagency groups, and the general public. The database provides species information, scientific reports, real-time search, spatial datasets, and distribution maps related to nonindigenous aquatic species. The database receives more than 80,000 reports of sightings annually.

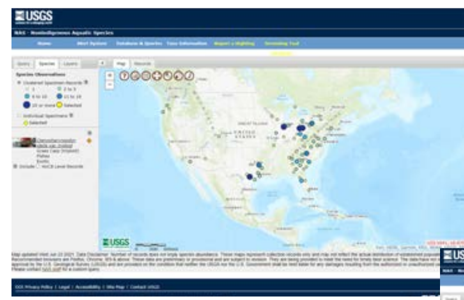
Red Lionfish

The red lionfish (*Pterois volitans*) is an invasive species native to the Indo-Pacific Ocean. The human-caused introduction and subsequent population increase of the species is now causing negative effects on marine ecosystems in the southeastern seaboard of the United States and the Caribbean Sea by competing with native predator fish and consuming smaller fishes. The USGS has developed tools and maps to assist resource managers in forecasting potential range expansion and indicate possible rapid response areas of invasive red lionfish following weather-related flooding, such as from hurricanes, for example, and after a new location is invaded (Witherington, 2012).

Photography by James Morris, Jr., National Oceanic and Atmospheric Administration

Alert Risk Maps

In order to respond quickly to aquatic invasive species, natural resource managers need to know when there is a new species sighting in or around their area and which waterbodies are at risk of invasion. The Nonindigenous Aquatic Species Alert System (U.S. Geological Survey, 2021l) provides a framework for the rapid release of information on new invasions as they are added to the nonindigenous aquatic species database. The system notifies registered users of new sightings of nonindigenous aquatic species as part of the national-scale early detection and rapid response framework and in support of several Federal partners, including the National Invasive Species Council, the Aquatic Nuisance Species Task Force, and other DOI agencies. The alert system is used to map and identify potential waterbodies (rivers, streams, lakes) at risk of invasion from newly introduced nonnative species providing a short-term risk assessment using the current extent of the spread of the species. The system provides credible scenarios of potential spread within a waterbody based on the behavior, habitat needs, and barriers that can limit spread of species. The maps created accompany alert emails and are an important component in building a rapid response system.



Flood and Storm Tracker

Storm surge and flooding can cause expansion of nonindigenous aquatic species into new waterbodies. Flood and Storm Tracker (U.S. Geological Survey, 2021m) maps combine potential flooding information for a storm with known locations of established or possibly established nonindigenous or invasive species based on the nonindigenous aquatic species database. Maps identify all drainages within a flood zone of a given storm event that have a nonindigenous species present or where there is a risk of introduction from surrounding watersheds. These maps help resource managers prioritize rapid response actions for areas most at risk of invasion, leading to the higher potential for eradication before invasive species can become established.

Improving Monitoring Efficiencies

Predicting how abundant and widespread a new invasive species population will become informs monitoring and control efforts. The rusty crayfish (*Faxonius rusticus*), native to the Ohio River basin, has been introduced in the John Day River, a major tributary of the Columbia River in Oregon. The invader can outcompete and displace native crayfish and reduce resource availability (U.S. Geological Survey, 2019b). The USGS is estimating the growth rate and spread of the rusty crayfish to help scientists and resource managers make decisions on how to allocate staff and funding for monitoring and management.

Buffelgrass in the Sonoran Desert

Buffelgrass is a nonindigenous, highly invasive perennial grass originally from the African savanna that was introduced into the United States as a forage grass that can outcompete native vegetation for soil nutrients and moisture. Buffelgrass is rapidly spreading across National Park Service (NPS) and adjacent lands in the Sonoran Desert in Arizona and California and can transmit fire quickly across the landscape. The USGS is working with the NPS and others on early detection and rapid response detection tools, such as sensors aboard unmanned aerial systems and high-resolution satellite imagery.

Photograph by Steve Hillebrand, U.S. Fish and Wildlife Service

Rusty crayfish. Photograph by Peter Pearsall, U.S. Fish and Wildlife Service.

Molecular Detection

Tracking the establishment and spread of existing and new invasive species is critical to effectively managing invasive species. In addition to standard means of monitoring, the USGS is developing new tools that involve molecular techniques to assist in the early detection of invasive species.

Environmental DNA

Environmental DNA (eDNA) is genetic material that is shed, excreted, or otherwise released into the environment by organisms that can be detected in water, soil, or even air. The USGS is a leader among Federal agencies in developing and improving eDNA tools for detecting invasive species, rare animals, plants, and microbes in the environment. The USGS is improving standards for sample collection and analysis and streamlining laboratory processes to speed sample processing and lower costs. To improve surveillance for nonindigenous aquatic species, the USGS is piloting an approach to share scientifically validated eDNA data in the nonindigenous aquatic species database to help resource managers track the movement of invasive species (U.S. Geological Survey, 2021e).

Rapid Detection Kits

Use of eDNA rapid detection kits require minimal training and are relatively inexpensive for resource managers to use to monitor new invasive populations and assess control-effort effectiveness. The USGS has developed assays that can take advantage of consumer off-the-shelf DNA and RNA detection kits to screen samples in less than an hour for specific organisms. These kits are being used to detect the fungus that causes rapid ´ōhi´a death in mature ´ōhi´a lehua trees in Hawaii (Hawaii Invasive Species Council, 2021). Portable eDNA detection kits have also been developed by the USGS for use by Federal and State law enforcement to detect invasive carps in baitfish shipments. Kits have also been developed so resource managers can monitor populations of Nile tilapia (*Oreochromis niloticus*) and guppy (*Poecilia reticulata*) the ecologically and culturally important anchialine ponds (enclosed ponds with an underground connection to the ocean) in Hawaii (U.S. Geological Survey, 2021e).

Rapid ´Ōhi´a Death

In 2014, a new disease caused by invasive fungi (*Ceratocystis* spp.), known as rapid ´ōhi´a death, was discovered in mature ´ōhi´a lehua trees in Hawaii (Hawaii Invasive Species Council, 2021). Based on recent and ongoing aerial surveys in 2019, more than 175,000 acres of forest contain ´ōhi´a showing symptoms of rapid ´ōhi´a death disease on the Island of Hawai´i (University of Hawai´i at Mānoa, 2021). Native and invasive ambrosia beetles (*Coleoptera: Curculionidae*) may help spread the fungi while boring into trees and creating dust that can spread to nearby trees or carrying the fungi on their bodies as they fly from tree to tree. The USGS is identifying the extent to which ambrosia beetles act as carriers of the fungal pathogens (Roy and others, 2020).

Photograph by Randy Bartlett, U.S. Geological Survey.

Detection of Elusive Species

Surveillance with eDNA allows for the presence of a species to be detected in an environment without having to collect the whole organism. Numerous projects are ongoing across the USGS to identify nonindigenous species through eDNA, including New Zealand mud snails (*Potamopyrgus antipodarum*), all invasive carps, and dreissenid (zebra and quagga) mussels (fig. 1). The USGS has developed and validated species-specific eDNA assays to monitor potential range expansion of Burmese python and bullseye snakehead (*Channa marulius*) in southern Florida (Hunter and others, 2019a, b). Assays for dreissenid mussels have been designed, validated, and used by the USGS (Barbour and others, 2018).

eDNA Metabarcoding

eDNA metabarcoding is used to identify all species whose DNA is present within a sample. Cutting-edge techniques of eDNA metabarcoding systems have been developed that can detect up to 37 species of native and nonindigenous fishes, including northern pike (*Esox lucius*) and brown trout (*Salmo trutta*), as well as the presence of other invasive species, such as the elodea (*Elodea* spp.) plants (also known as waterweed) in water samples collected from lakes and streams. The USGS works extensively with the FWS to validate and develop methods to process ichthyoplankton tows in the Great Lakes and other waterbodies to detect nonindigenous aquatic species as well as validate approaches used in metabarcoding to improve detection probabilities for invasive species from environmental samples. The USGS is using new eDNA metabarcoding methods on samples collected from eelgrass (*Zostera* spp) meadows in Alaska and the U.S. Virgin Islands to determine the presence of two classes of pathogenic organisms known to have caused decreases in the populations of eelgrass in other parts of the country. These new methods are efficient and provide an accurate understanding of how disease organisms are distributed and their status as invasive species.

A filter used to collect a sample for analysis of eDNA in the Little Calumet River, Indiana, is carefully folded. Photograph by Barbara J. Mahler, U.S. Geological Survey.

Statistics and Methods Improvement

The ability to replicate a laboratory test and obtain consistent results while accounting for false detections is fundamental for credible scientific analysis and diagnosis. The USGS has developed laboratory-based protocols for eDNA that ensure repeatable and reproducible results for detection of dreissenid mussels (Sepulveda and others, 2020); these protocols have been cross-validated with other laboratories to assess their accuracy and false positive rates. The USGS has also created statistical methods to account for false negative detections and to assess minimum numbers of eDNA samples required (Stratton and others, 2020).

Robotic Water Sampling

Autonomous water sampling (robotic) technologies present an opportunity to overcome challenges associated with traditional manual eDNA sampling. The USGS is integrating robots designed by the Monterey Bay Aquarium Research Institute (MBARI) into the USGS streamgage network to cost-effectively collect eDNA for invasive species detection. For example, scientists placed robots at two streamgages in the Yellowstone River in Montana to monitor for DNA of the fish pathogen *Tetracapsuloides bryosalmonae*, the causative agent of an extensively widespread fish die-off in 2016.

Photograph by Cheryl Miller, U.S. Geological Survey.

eDNA samples collection in the Little Calumet River within Indiana Dunes National Park, Indiana, as a part of Unionidae mussel restoration project. Photograph by Kasia Przybyla-Kelly, U.S. Geological Survey.

Aquatic Invasive Species

Aquatic invasive species cause significant ecological and economic losses to aquatic ecosystems, water quality, and fisheries. They also diminish opportunities for recreational uses of valued aquatic resources. USGS research is focused on characterizing the spread and distribution of aquatic invasive species, improving containment and control strategies, and developing decision support frameworks to assist managers in prioritizing management actions.

Invasive Carps

Invasive carps are fast-growing and prolific feeders that outcompete native fish, threaten native mussels and plants, and adversely affect economically important commercial and recreational fisheries. Successful management of these invaders requires tracking populations, preventing future spread, minimizing their effects, and reducing population levels through novel control tools (for example, pesticide registration).

Manifold system to evaluate carbon dioxide as a fish deterrent in Morris, Illinois. Photograph by the U.S. Geological Survey.

Methods for Control of Invasive Carps

There is an increased threat of the invasive bighead, black, and silver carps found in the Mississippi River Basin, entering the Great Lakes, and spreading in other basins. In collaboration with States and other Federal agencies, the USGS is developing and testing new and existing deterrent and control technologies (U.S. Geological Survey, 2021p). Behavioral (including carbon dioxide) and multisensory (such as BioAcoustic Fish Fence by Fish Guidance Systems Ltd.) deterrents to discourage invasive carps from passing upstream through strategic locks and dams have undergone or are undergoing large-scale field tests. A specialized, large-scale fishing technique known as the modified unified method and adapted from a method used in Chinese aquaculture (Li and Xu, 1995) has been and continues to be studied by the USGS in reservoirs and river reaches where these invasive carps are abundant (Chapman, 2020).

Lethal controls of invasive carps developed by the USGS, including nonselective general piscicides such as the pesticide Carbon Dioxide Carp (U.S. Geological Survey, 2021j) developed in collaboration with the FWS and recently registered with the U.S. Environmental Protection Agency, are available for use by States and other agencies. The USGS is also developing and testing pesticides designed to selectively target invasive carps and that take advantage of either greater sensitivity of invasive carps to certain chemicals or their specialized feeding strategies. Bighead and silver carps filter small particles out the water, grass carp feed on aquatic vegetation, and black carp use molar-like teeth to crush mollusks. These selective pesticides could be integrated with other control techniques (for example, deterrents and specialized fishing) to effectively manage invasive carp populations while minimizing adverse effects on native fishes.

Field testing of the deployment of a carbon dioxide infusion system as a chemosensory deterrent to invasive carps in Morris, Illinois. Photograph by the U.S. Geological Survey.

Scientists from the U.S. Fish and Wildlife Service and the U.S. Geological Survey work together to tag a silver carp caught in the upper Mississippi River near La Crosse, Wisconsin. Photograph by the U.S. Geological Survey.

Monitoring Invasive Carp Movement

Understanding the movement and habitat use of invasive carps is critical to informing decisions about monitoring and the application of controls, including removal by specialized fishing techniques, deterrents, and piscicides. The USGS, in collaboration with State and Federal partners, is tracking invasive carps by using acoustic transmitters attached to the fish and detected by a basinwide, multiagency network of telemetry receivers (U.S. Geological Survey, 2021g). These data are analyzed and used to assess the movements and spatial distributions of invasive carps to inform adaptive management efforts; the data are also used to understand fine-scale movements, such as around navigation locks, to inform development and testing of behavioral deterrents. The USGS has installed and maintains real-time telemetry receivers and hosts data from receivers deployed in tributaries to Lake Erie where management agencies can target control of Grass Carp (Harris and others, 2019).

Lethal Controls of Black Carp

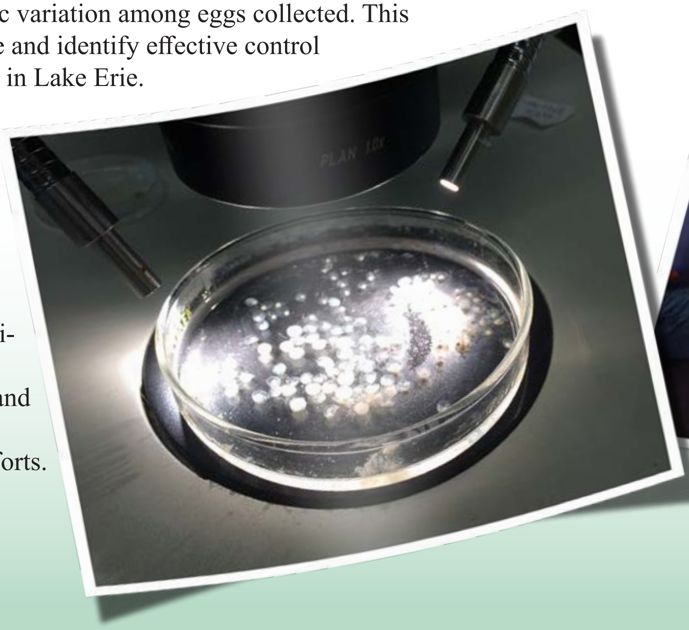
Black carp feed on native mussels and snails. The USGS is developing a toxic bait that can be attached to the shell of a mussel or snail or as a prepared hard bait that only takes effect when black carp crushes and eats the bait (U.S. Geological Survey, 2021b).

Photograph by U.S. Geological Survey.

Grass Carp Control in the Great Lakes

The USGS has identified where, when, and under what specific conditions grass carp reproduce in two tributaries of Lake Erie. Grass carp are prolific breeders and capable of consuming up to their body weight per day in plant material. Transdisciplinary efforts within the USGS have led to ongoing projects to estimate effective genetic population size based on genetic variation among eggs collected. This research will help determine population size and identify effective control measures to reduce and eradicate grass carp in Lake Erie.

Collaboration between the USGS and the University of Toledo has led to the incorporation of new submersed aquatic vegetation field data into existing aquatic vegetation map results to assess surface estimation of submersed aquatic vegetation and to identify key species composition for placement of bait deployment (U.S. Geological Survey, 2021a). Additionally, the USGS has identified a bait that attracts grass carp and is working with the States of Michigan and Ohio to use that bait to improve removal efforts.



Northern Pike

Northern pike is a large predatory fish that is native to the northern United States and Canada but that has been widely introduced into the western United States, including through illegal stocking in south-central Alaska (U.S. Geological Survey, 2019a). Northern pike are fish-eating ambush predators that can severely affect valuable native and recreational fisheries (He and Kitchell, 1990; Sepulveda and others, 2015). The USGS is working with State and Federal agencies to examine the effects of northern pike on native salmonids and other fishes in Alaska and the Pacific Northwest and develop eDNA analyses to track their distribution and spread.

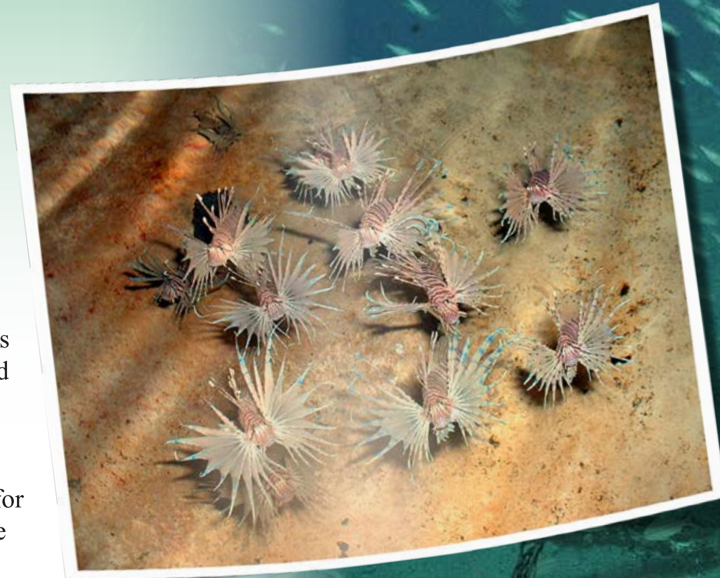
Lake Trout

Lake trout (*Salvelinus namaycush*) are large predacious salmonids native to deep lakes of the northern United States and Canada, but they were stocked elsewhere for recreational fishing and have expanded their range to more than 200 waterbodies in the western United States, devastating valuable native and recreational fisheries (U.S. Geological Survey, 2021o). USGS research on invasive lake trout has focused on efforts to understand their effects to aquatic ecosystems, to develop and test control measures to reduce their abundance and spread, and to assess invasion risk for conservation planning and mitigation. The USGS is working with the National Park Service (NPS) and the FWS to reduce invasive lake trout populations in two lakes in Glacier National Park while protecting and restoring threatened native bull trout (*Salvelinus confluentus*) populations (U.S. Geological Survey, 2021f). The USGS is also researching the effects of lake trout on aquatic food webs for conservation management strategies in several lakes throughout the northern Rocky Mountains.

Aerial view of backwater habitat for invasive northern pike off Alexander Creek in the Susitna Basin of south-central Alaska. Photograph by Adam Sepulveda, U.S. Geological Survey.

Lionfishes

Lionfishes (*Pterois volitans* and *P. miles*) are native to the Indian Ocean but are now established in the Gulf of Mexico, the Caribbean Sea, and the southeastern Atlantic Coast of the United States. Since first reported in 2000 off the southeastern Atlantic Coast of the United States (Morris and Whitfield, 2009), lionfishes have become abundant in some areas and are now widely dispersed (Hare and Whitfield, 2003; Schofield, 2009). Lionfishes are voracious predators, with venomous spines, that consume and compete with native species and have few predators in U.S. waters. The USGS is working with State and Federal agencies and citizen scientists to track distribution of lionfishes, research the biology and ecology of the species, and develop innovative methods for trapping the species. These methods include using remote underwater cameras with software to identify lionfishes and distinguish them from other species to exclude from a "smart" trap.



USGS Fish Slam

In Florida, fish slams are successful citizen science events that assist scientists and natural resource managers track nonindigenous fish species. To date, the USGS and Federal, State, Tribal, and private partners have organized 10 fish slams, with nearly 100 participants from 21 organizations (U.S. Geological Survey, 2021h). Participants have sampled nearly 200 unique sites, captured 36 nonindigenous fish species, and generated more than 600 records for the USGS nonindigenous aquatic species database (U.S. Geological Survey, 2021n). Hundreds of specimens have been donated to natural history museums around the country, and many more are used by researchers.

Photograph by Pamela J. Schofield, U.S. Geological Survey.

A red lionfish caught in a net. Photograph by the U.S. Geological Survey.

Sea Lamprey

The parasitic sea lamprey invaded the upper Great Lakes after improvements were made to the Wellend Canal (a shipping canal that connects Lake Ontario and Lake Erie and enables ships to ascend and descend the Niagara Escarpment and bypass Niagara Falls). By the mid-20th century, the species had devastated valuable native fisheries and coastal economies (Lawrie, 1970; Scott and Crossman, 1973; Smith and Tibbles, 1980; Courtenay, 1993; Page and Laird, 1993). The USGS supports binational sea lamprey control in the Great Lakes by the FWS and the Department of Fisheries and Oceans Canada by working with the Great Lakes Fishery Commission, State, Federal, and Tribal agencies, academic institutions, and nongovernmental organizations to provide science on sea lamprey biology, detection and control technologies, and lampricide development and registration (U.S. Geological Survey, 2021i).

The USGS researches ways to improve and evaluate new lampricide formulations as well as regulatory support to maintain the United States and Canadian registrations of lampricides used in the sea lamprey control program. The USGS also provides critical research to evaluate effects of lampricides on nontarget organisms and has initiated a program to discover and evaluate next-generation lampricides to ensure continuation of highly selective control. The USGS is evaluating the use of eDNA to monitor lamprey populations and is developing nonpesticidal control and detection technologies by means of a novel trap and electrical guidance array capable of removing 75 percent of sea lamprey from a stream with minimal effects to native species and streamflow (U.S. Geological Survey, 2017a).

A closeup of an invasive sea lamprey. Photograph by the U.S. Geological Survey.

Zebra and Quagga Mussels

Invasive zebra and quagga mussels originating in Eurasia affect industrial and municipal infrastructure and recreational water use in waterbodies in the United States and severely alter aquatic ecosystems, costing millions of dollars annually (Nalepa and Schloesser, 1993; Schloesser and Nalepa, 1994). The USGS is collaborating with numerous Federal and State partners to improve detection, rapid response, and control of dreissenid mussels in the Great Lakes and Upper Mississippi River basins, including evaluating the efficacy of molluscicides. The USGS is collaborating with the Bureau of Reclamation to develop a carbon dioxide delivery system to prevent biofouling by dreissenids at hydropower dams. The USGS is also working with State partners in Minnesota to refine treatment strategies for registered pesticides, thereby reducing control costs and adverse nontarget effects.

In 2016, the first detection of zebra mussel larvae was documented in Montana, resulting in strengthened Federal Government efforts, in coordination with State and Tribal agencies, to address invasive mussels in the northern Rocky Mountains (Schmidt and McLane, 2017). In support of this effort, the USGS evaluated genetic markers for early detection of zebra mussels and is working to improve eDNA sampling and analysis protocols and early-detection monitoring plans.

The Columbia River Basin (CRB) in the Pacific Northwest now stands as one of the few areas in the United States not invaded by dreissenid mussels. Although not yet established in Montana, the discovery of larval invasive mussels in 2016 raised concerns across the region regarding the introduction of invasive mussels into CRB waters. The USGS is working with the private sector and State and Tribal agencies to start early detection monitoring for dreissenid mussels throughout the region and to evaluate early detection monitoring programs as dreissenid mussels are detected. To increase the probability of detecting invasive mussel infestations in the CRB, the USGS is collaborating with scientists from Canada to develop decision-support tools to help formulate a coordinated strategy for monitoring activities for dreissenid mussels. The goal is to provide cost-effective monitoring tools for invasive mussels that help resource managers allocate limited resources to areas with high invasion risk.

Zebra mussels from Lake Huron. Photograph by Amy Benson, U.S. Geological Survey.

Invasive Grasses and Vegetation

Invasive plants have dramatic effects on landscapes, especially in the western United States where there is increased pressure on native plants from drought, increased fire vulnerability, changed ecosystem structure, displaced native plants and wildlife, and diminished quality of forage available for livestock grazing. USGS researchers are working with DOI land managers and Federal and State partners to find solutions to these growing problems.

Annual Grasses

The expansion and dominance of cheatgrass, medusahead (*Taeniatherum caput-medusae*), and other invasive annual grasses in rangeland and sagebrush ecosystems are one of the invasions that have had the most effects in the United States (Kennedy, 2018). These invasive grasses thrive in disturbed areas where they can spread through human-mediated transport and transportation corridors. Invasive grass species can become dominant, create more fuel for rangeland fires, and reduce wildlife habitat, recreational opportunities, and livestock forage. The USGS is developing various tools and strategies that help Tribal, Federal, State, industry, and private land managers design and implement sustainable rangeland practices. These tools include effective restoration and rehabilitation projects and practices to restore native vegetation to reduce invasive grasses and increase postfire resilience. These strategies include modeling recovery times after fires, examining links of wildfire patterns across the Great Basin with changing sage-grouse populations and climate, and developing fire management protocols that include alternatives to chemical and mechanical control methods (Remington and others, 2021).

Salt Cedar

Salt cedar, which is native to southern Europe and north Africa, is one of the most broadly distributed plants in the western United States and may increase water loss and soil salt content, which can inhibit other plants (Shafroth, 2010). The USGS is a leader in understanding the distribution and effects of invasive salt cedar on ecosystems in the western United States (U.S. Geological Survey, 2017b). In collaboration with multiple partners, the USGS is studying the effectiveness of releasing a species of beetle as a biological control to reduce salt cedar populations. The USGS is also using remote sensing to document changes in riparian plant communities and, in cooperation with the University of Arizona, has created an interactive riparian vegetation data explorer with data from 2000 for the Colorado River and its tributaries in Arizona (Vegetation Index & Phenology Lab, 2021). These studies provide valuable information to aid resource managers in planning and prioritizing salt cedar control and native plant restoration.

Invasive Aquatic Plants

Invasive aquatic plants can impede recreational use of waterbodies, clog waterway navigation, reduce native plants, and degrade habitat for fish and wildlife. Across the Nation, the USGS is assisting land and water managers in ongoing efforts to manage nonindigenous aquatic plants.

Common Reed

The nonnative common reed, or phragmites, is invading coastal wetlands, riparian habitats, lakes, ponds, and wetland areas throughout the binational Great Lakes, along the marine coasts, and across our Nation's interior. Its rapid growth rate and large size help it outcompete native plants, degrade fish and wildlife habitat, reduce recreational opportunities, increase fire hazard, and reduce property values (Swearingen and Saltonstall, 2012; Avers and others, 2014). The USGS works with DOI partners (such as the FWS and NPS) and State and Provincial partners through the Great Lakes Commission (GLC), academia, nongovernmental organizations, and private landowners to maximize the collective effects of efforts to find solutions for managing phragmites. In partnership with the GLC, the USGS contributes to the regional science-management discussion through the Great Lakes Phragmites Collaborative and directly supports the development of the phragmites adaptive management framework, which applies science to reduce the uncertainty of which treatment approach works the best. In addition, the USGS is exploring the effects of water-level variation on the effectiveness of phragmites treatment and developing new and innovative biocontrol approaches that are based on plant-microbe relations and genetic expression of the plant to provide species-specific tools for resource managers.

Phragmites australis on the shore of Lake St. Clair. Photograph by Kurt Kowalski, U.S. Geological Survey.

Invasive Plants in Hawaii

In the Hawaiian islands, invasive plants threaten healthy ecosystems and can cause the extinction of native plants and animals. The USGS is developing models and maps of the distribution of and habitat suitability for invasive plant species. Using future climatic scenarios, scientists are predicting future distributions of invasive plants to provide information for detection, monitoring, and control so resource managers can more effectively target Hawaii's most disruptive invaders and protect endemic species.

Photograph by Lucas Fortini, U.S. Geological Survey.

Waterweed and Water Hyacinth

The aquatic plant waterweed is a potential invader to arctic and subarctic ecosystems and is already established in some parts of Alaska (Larsen and others, 2020). Waterweed can alter ecosystem processes and food web structure; yet, little is known about the effects on fish performance. The USGS is studying the effects of waterweed on vulnerable juvenile salmon in the early stages of an invasion in Alaska.

Water hyacinth (*Eichhornia crassipes*) is a floating invasive aquatic plant, particularly problematic in Florida, Louisiana, and Texas, that forms impenetrable floating mats of vegetation that can block sunlight to submerged plants, reduce oxygen for aquatic wildlife, and impede recreation and waterborne transit (Lowe and others, 2000). With climate change, the species is moving northward and has now been discovered in Wisconsin (U.S. Geological Survey, 2021d). The USGS is working to predict the spread of water hyacinth and other invasive plants through flooding from storms and hurricanes.

Eurasian Watermilfoil

Many aquatic plants are transported to waterbodies through human activity such as boating. One of those plants is Eurasian watermilfoil (*Myriophyllum spicatum*), which competes with native aquatic vegetation by growing earlier in the year and blocking light to other plants in the water. It can also hybridize with the native northern watermilfoil (*M. sibiricum*). The USGS has developed eDNA techniques to detect Eurasian watermilfoil DNA in waterbodies of Yellowstone National Park to help resource managers better detect this species and enable rapid response before there are costly effects (Newton and others, 2016).

A sea of the invasive species giant salvinia, hydrilla, and water hyacinth clogs one end of Lake Murphy, Louisiana. Photograph by Alex Demas, U.S. Geological Survey.

Brazilian Waterweed

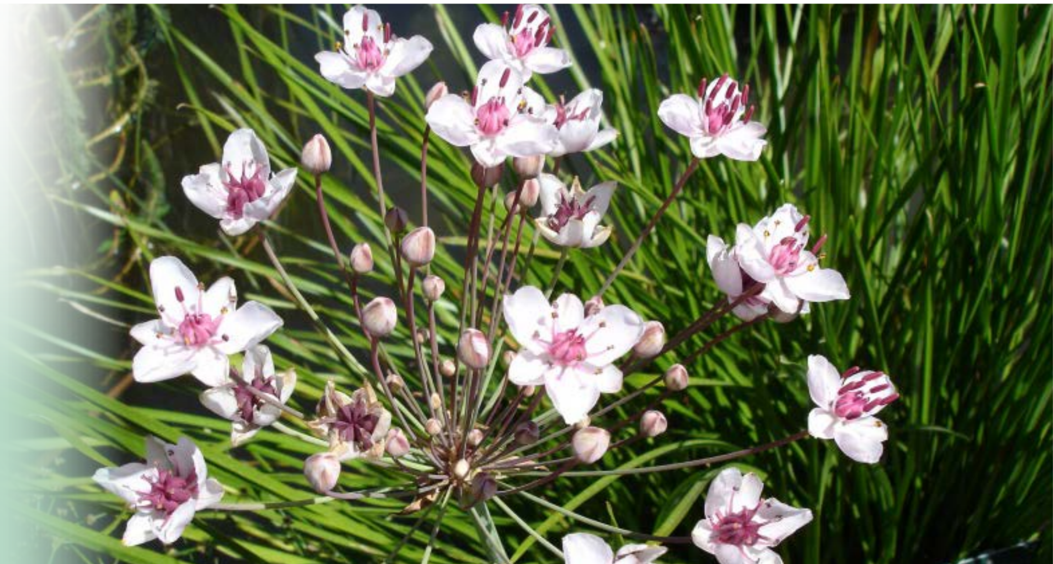
Brazilian waterweed is among the most common of several nonindigenous submerged aquatic plants found in the Sacramento-San Joaquin Delta of California and is decreasing river water turbidity and interfering with marsh formation processes by trapping sediment. Waterways of the delta contain threatened and endangered fish that rely on turbid waters to feed safely and marshes that require sediment deposition to keep surface elevations in pace with sea-level rise. The USGS is quantifying the amount of sediment trapped by invasive submerged aquatic plants in the entire region to help resource managers focus control efforts on key habitats in the delta.

Melaleuca

In Florida, melaleuca is an invasive tree in the greater Everglades ecosystem that displaces native plants and wildlife and is highly detrimental to ecosystem restoration efforts. The USGS is using field data from aircraft and unmanned aerial system surveys to quantify the abundance, distribution, and potential spread of melaleuca in southern Florida to aid in removing these invasive trees at the lowest cost possible.

Flowering Rush

Some invasive species, although long established in the United States, continue to spread to new areas. Of these, flowering rush (*Butomus umbellatus*) is of special concern within the upper Mississippi River system. Easily spread by recreational boating, this species continues to move upriver within the river system. Using historic and current high-resolution imagery of the upper Mississippi River system, the USGS is working to better understand where this population is emerging and how it is spreading through the system.



Invasive Reptiles

Invasive reptiles are an increasing problem across the United States, putting at risk native species and human infrastructure. Tracking the establishment and spread of existing and new invasive reptile species is critical to effective management. The USGS is developing novel tools to assist in the early detection and rapid response of invasive reptiles.

Black and White Tegu

The Argentine black and white tegu is a large omnivorous lizard native to South America and is common in the international pet trade. There are at least three established populations of tegus in southern Florida and one in Georgia, all likely resulting from escaped or released pets. Tegus eat a variety of plants and animals but specialize in consuming eggs from bird and reptile nests. Research by the USGS demonstrated that conditions suitable for tegu survival may exist across the southern one-third of the continental United States (Enge, 2007; Krysko and others, 2011; Pernas and others, 2012; Mazzotti and others, 2015; Wood and others, 2018; Haro and others, 2020). The USGS is developing and testing methods for detection and control of tegus, determining the species' thermal tolerances, and assessing risks to the greater Everglades ecosystem and beyond.

Invasive black and white tegu lizard. Photograph by the U.S. Geological Survey.

Burmese Pythons

Burmese pythons are large invasive snakes, which can exceed 18 feet in length and 150 pounds in weight. Research by the USGS has focused on methods for detection and control, predicting the potential range of the species in the United States, understanding their thermal tolerances, and assessing the risks of pythons and other giant constrictors. The USGS research aims to aid in the management of Burmese pythons in Everglades National Park, Big Cypress National Preserve, and other DOI lands in southern Florida (Snow and others, 2007; Reed and Rodda, 2009). The USGS and partners documented that Burmese pythons have devastated the mammal communities in Everglades National Park (Dorcas and others, 2012) and are known to have consumed several endangered species, including wood storks (*Mycteria americana*) and Key Largo woodrats (*Neotoma floridana smalli*).

Nidoviruses are a group of viruses that can cause sometimes fatal pneumonia in snakes. These viruses have been identified in captive Burmese pythons in southern Florida and in free-ranging Burmese pythons in the Everglades (Blahak and others, 2020). The USGS is characterizing the prevalence of the virus in free-ranging Burmese pythons in southern Florida to assist resource managers that are concerned about the risk of transmission to native snakes.

A Burmese python investigating its surroundings in southern Florida. Photograph by Melia G. Nafus, U.S. Geological Survey.

Photograph by Bob Dusek, U.S. Geological Survey.

Invasive Species and Human Health

Several invasive mosquitoes have become established in Hawaii, including yellow fever (*Aedes aegypti*), forest day (*A. albopictus*), and Asian bush (*A. japonicus*) mosquitoes. Aedes mosquitoes are aggressive human biters and vectors of human viral diseases, such as yellow fever, dengue, zika, and chikungunya. The USGS, in collaboration with the NPS, has documented the distribution of *Aedes* mosquitoes in NPS lands and surrounding areas and evaluated methods for detection and monitoring (U.S. Geological Survey, 2016, 2021k). This science provides data and analysis to assist the NPS and the Hawaii Department of Health with protecting the health of park staff and visitors and the public.

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Descriptions and credit for inset photographs

Page	Description/caption
5 top	The roots of an Oriental bittersweet are being examined; expansive bittersweet roots provide competitive advantage to the plant over native vegetation to extract soil resources. Photograph by Wendy Smith, National Park Service.
5 bottom	Invasive species samples placed on a microwell plate for development of a next-generation DNA sequencing method. Photograph by the U.S. Geological Survey.
6	Closeup of an invasive brown treesnake. Photograph by Bjorn Lardner, U.S. Geological Survey.
7 top left	The web page of the interactive map of the U.S. Geological Survey’s Nonindigenous Aquatic Species database, showing where zebra mussels have been found. Photograph by Susan L. Meacham, U.S. Geological Survey.
7 top right	Screenshot of the interactive map of the U.S. Geological Survey’s Nonindigenous Aquatic Species Alert System.
7 bottom right	Screenshot of the interactive map of the U.S. Geological Survey’s Nonindigenous Aquatic Species Flood and Storm Tracker.
7 sidebar	Adult lionfish. Photograph by James Morris, Jr., National Oceanic and Atmospheric Administration.
8 sidebar	Invasive buffelgrass. Photograph by Steve Hillebrand, U.S. Fish and Wildlife Service.
9 top left	Collecting a stream sample in the Boise River, Idaho, for environmental DNA (eDNA) testing. Photograph by Matthew Laramie, U.S. Geological Survey.
9 top right	“Lab in a suitcase” set up in the field to test samples for the *Ceratocystis fimbriata* fungus responsible for rapid ´ōhi´a death. Photograph by Carter Atkinson, U.S. Geological Survey.
9 sidebar	´Ōhi´a is a native tree important to the ecology and culture of Hawaii that is at risk from a tree-killing fungus. Photograph by Randy Bartlett, U.S. Geological Survey.
10 top	eDNA sample collection at Grant Point in Izembek National Wildlife Refuge, Alaska. This eDNA sampling is part of a project looking for eelgrass pathogens in the North Pacific. Photograph by David Ward, U.S. Geological Survey.
10 bottom	A portable eDNA detection kit is used in a lab. Photograph by Mike Caucutt, U.S. Geological Survey.
11 sidebar	A Monterey Bay Aquarium Research Institute environmental sample processor installed in a U.S. Geological Survey streamgage. Photograph by Cheryl Miller, U.S. Geological Survey.
14 sidebar	Invasive black carp. Photograph by the U.S. Geological Survey.
14 bottom left	Grass carp eggs being examined under a microscope to determine developmental stage. Photograph by Patrick Kocovsky, U.S. Geological Survey.
14 bottom right	Sampling for grass carp larvae and eggs in the Sandusky River, Ohio, collected using a set of bongo nets, so named because they resemble bongo drums. The nets are deployed one above the other so that one samples the surface water while the other samples deep water. Photograph by the U.S. Geological Survey.
15 top	A northern pike. Photograph by Susan Doty, U.S. Geological Survey.
15 bottom	A lake trout, a species invasive to water bodies of Glacier National Park, Alaska. Photograph by Nicole King, University of Toledo, under contract to the U.S. Geological Survey; in the public domain.
16 top	A group of juvenile lionfish. Photograph by James Morris, Jr., National Oceanic and Atmospheric Administration.
16 sidebar	Citizen scientist showing a sample of an invasive species collected during a Fish Slam event. Photograph by Pamela J. Schofield, U.S. Geological Survey.

Page	Description/caption
18	A moss ball sold in pet stores containing an invasive zebra mussel. Photograph by Wes Daniel, U.S. Geological Survey.
19 background	Defoliated tamarisk (orange/brown vegetation) after application of biological control along the Colorado River, Utah. Photograph by Patrick B. Shafroth, U.S. Geological Survey.
19 top	Close up of invasive cheatgrass. Photograph by Justin L. Welty, U.S. Geological Survey.
19 bottom	Defoliated tamarisk. Photograph by Patrick B. Shafroth, U.S. Geological Survey.
20 sidebar	Invasive common lantana on the island of Lāna´i, Hawaii. Photograph by Lucas Fortini, U.S. Geological Survey.
22 top	Brazilian waterweed collected using a threshing rake in the Sacramento-San Joaquin Delta, California. Photograph by the U.S. Geological Survey.
22 middle	The invasive tree melaleuca threatens native wildlife and habitat in the Everglades, Florida. Photograph by the U.S. Geological Survey.
22 bottom	Flowering rush. Photograph by Bouba, licensed under the Creative Commons Attribution-Share Alike 3.0 Unported; https://commons.wikimedia.org/wiki/File:Butomus_umbellatus.jpg.
23	Black and white tegu lizard in the grass in the Everglades, Florida. Photograph by Emma Hanslowe, U.S. Geological Survey.
24 top	A Burmese python coiled in the grass in the Everglades, Florida. Photograph by Bryan Falk, U.S. Geological Survey.
24 bottom	Mosquito biting a human hand. Photograph by Bob Dusek, U.S. Geological Survey.

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