objeNational Control and Management Plan
for
Members of the Snakehead Family (*Channidae*)

Drawing by: Susan Trammell

DRAFT

Submitted to the Aquatic Nuisance Species Task Force
Prepared by the Snakehead Plan Development Committee

2014

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In Dedication to Walt Courtenay

Walter R. Courtenay Jr., a leader in aquatic invasive species research in the U.S. since the early 1970s, passed away on January 30, 2014. He was a passionate, dedicated, productive, vocal, and, some would say, much opinionated scientist who will remain a hero to many of us. His drive to better understand the species in the snakehead family and the risks they posed to North America set forth a pathway for ecological risk assessments. The wealth of information he compiled and provided to the scientific and management community was essential to developing this Snakehead Plan. Therefore, this document is dedicated to him and is a tribute to his career. He will be very much missed by his colleagues, most of whom were also his friends.

Executive Summary

The introduction and establishment of northern snakehead (*Channa argus*) into waterways of the United States (U.S.) has received a great deal of media, public, and political attention since 2002. The northern snakehead is a popular food fish throughout its native distribution in Asia and was imported into the U.S. for the live-food fish market until 2002, when the U.S. Fish and Wildlife Service (USFWS) added northern snakehead to its List of Injurious Species and prohibited importation and interstate transport under the Lacey Act, (18 U.S.C. 42).

Prior to 2002, the occurrence of northern snakehead in the U.S. was relatively limited and consisted of low numbers of individuals in discrete locations (California, Florida, Massachusetts, and North Carolina). No evidence was found that these populations were self-sustaining. However, self-sustaining populations of blotched snakehead (*Channa maculata*) and bullseye snakehead (*Channa marulius*) occurred in Hawaii and Florida, respectively. The first reproducing population of northern snakehead was discovered and later eradicated in a small pond in Crofton, Maryland in 2002. Two years later northern snakehead was collected in a pond near Wheaton (MD) and then in several tributaries of Potomac River. Since 2004, the species has established and expanded its population from only a few tributaries to most tributaries extending from Great Falls, Virginia (above Washington, D.C.) to the mouth of the Potomac River. It was initially thought that higher salinity in the lower Potomac River and Chesapeake Bay would prevent snakehead species from expanding beyond the mouth of Potomac River. This assumption no longer appears valid as northern snakehead have been captured in several other river drainages of the Chesapeake Bay. Other established northern snakehead populations have been found in the states of New York, New Jersey, Pennsylvania, Delaware, and Arkansas.

The 108th Congress in 2005 requested that the USFWS address concerns about the introduction of northern snakehead. Senate Report 108-341, Department of the Interior and Related Agencies Appropriations Bill states, “the Committee is concerned by the recent discoveries of northern snakehead in the Potomac River and its potential impact on native fish populations through predation, food and habitat competition, or the introduction of diseases and parasites. The Committee directs the USFWS to submit a report to Congress on steps the Agency is taking to identify, contain, and eradicate the species.” In response to this Congressional mandate, the USFWS assembled a Northern Snakehead Working Group (NSWG) to provide input on the development of a Northern Snakehead Control and Management Plan (Plan). This Plan was developed with the input of the NSWG and other northern snakehead experts to guide the USFWS and other interested parties in managing and controlling existing populations, and preventing the spread and introduction of this species into additional areas of the U.S.

In 2011, the Mississippi River Basin Panel requested that the Aquatic Nuisance Species Task Force (ANSTF) update the 2005 Plan to include additional snakehead species that are, or have the potential to become invasive in United States waters. Therefore, this plan has been expanded to include all snakehead species to correspond with the Lacey Act.

However, due to a lack of available information on most snakehead species, the life histories of only three species are described in this management plan. They include the northern snakehead, giant snakehead (*Channa micropeltes*), and bullseye snakehead. However, the goal and objectives of this plan are applicable to all snakehead species with the assumption that the pathways of introduction and management options are similar for all snakehead species.

The goal of the revised Plan is to use the best available science and management practices to prevent the future introduction of snakehead into new areas, contain and, where possible, eradicate newly established and localized populations, and minimize impacts in areas where they are established and eradication is not feasible. The following is a list of objectives set forth by this plan:

1. Prevent importation into the U.S. by refining regulations and improving compliance and enforcement.
2. Contain the expansion of snakehead within the U.S. by assessing the risk of establishment and developing an effective snakehead surveillance program that can detect new introductions at a stage where populations are able to be eradicated.
3. Develop long-term adaptive management options to mitigate potential impacts of snakehead in U.S. waters where eradication is not possible.
4. Conduct research to better understand the pathways of spread and potential impacts of snakehead on aquatic ecosystems, as well as to develop more effective surveillance, control, and eradication methods.
5. Develop effective outreach materials to help prevent new introductions of snakehead within the U.S. and control the anthropogenic spread of established populations.
6. Review and assess progress of the Plan.

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Purpose of Management Plan

The purpose of this Snakehead Control and Management Plan (Plan) is to guide Federal agencies and other applicable stakeholders in managing invasive snakehead already established in U.S. waters as well as prevent the further spread and introduction of these fish into other waterways. Snakeheads are a popular food fish that is native to Asia. Over the past two decades, snakeheads have been imported into certain ethnic markets in the U.S. for the live-food fish market and are one of the primary pathways of introduction into the United States. Species of snakeheads were also imported via the aquarium trade. Prior to 2002, there had been sporadic single occurrences of northern snakehead in California, Florida, Massachusetts, and North Carolina that appear to be the result of releases of single fish. There was no indication of established, reproducing populations. Other species of snakehead (bullseye snakehead and blotched snakehead) occurred in sub-tropical or tropical habitats of the United States; there was no indication these species would survive in temperate ecosystems that dominate the United States. However, in 2002, a self-sustaining population of northern snakehead was discovered and eradicated in a small pond in Crofton, Maryland. In 2002, the USFWS prohibited the importation and interstate transport of all snakehead species under the Lacey Act. Subsequently, in May 2004, northern snakehead were discovered in the main stem tidal freshwater Potomac River near Mount Vernon, Virginia and have since increased in range and abundance. Additional established populations have been detected in Arkansas, Delaware, Maryland, New Jersey, New York, Pennsylvania, and Virginia. Three other snakehead species have also been found in the United States. The blotched snakehead has established on Oahu, Hawaii for over a century, deliberately introduced for its use as a food fish. Bullseye snakehead is now established in southern Florida as a result of illegal stocking. The giant snakehead has been reported in Maine, Maryland, Massachusetts, Rhode Island, Tennessee, and Wisconsin; however, there is no evidence that any of these introductions have led to an established population.

In 2005, Congress requested that the USFWS address concerns about the introduction of northern snakehead. Senate Report 108-341, on the Department of the Interior and Related Agencies Appropriations Bill (2005) of the 108th Congress states, "[t]he Committee is concerned by the recent discoveries of northern snakehead in the Potomac River and its potential impact on native fish populations through predation, food and habitat competition, or the introduction of diseases and parasites. The Committee directs the U.S. Fish and Wildlife Service to submit a report to Congress on steps the Agency is taking to identify, contain, and eradicate the species."

In response to this Congressional mandate, in 2006 the USFWS assembled a Northern Snakehead Working Group (NSWG) to provide input on the development of a management plan, which would become the Snakehead Control and Management Plan (Plan). The intent of the Plan was to identify action items to guide agency activities and funding priorities and to focus the efforts of other stakeholders and non-governmental organizations (NGOs). The plan's emphasis was on specific control priority action items needed in the Potomac River and northeast region. It also addressed national prevention,

early detection and rapid response, control, research, and education and outreach priorities, should additional snakehead populations be discovered.

A draft Plan report was completed in February of 2007. An update to the report was completed in March 2011. As a result of the continued spread of the northern snakehead and risk of other snakehead species entering the country, the Mississippi River Basin Panel (MRBP) requested that the Aquatic Nuisance Species Task Force (ANSTF) update the Plan to address additional snakehead species that have the potential to become invasive in U.S. waters. The MRBP specified ten species at highest risk for establishment based on Herborg et. al. 2007. These species included: the blotched snakehead (*Channa maculata)*, bullseye snakehead (*Channa marulius)*, chevron snakehead (*Channa striata*), Chinese snakehead (*Channa asiatica*), giant snakehead (*Channa micropeltes)*, golden snakehead (*Channa stewartii*), Niger snakehead (*Parachanna africana*), northern snakehead (*Channa argus)*, rainbow snakehead (*Channa bleheri*), and spotted snakehead (*Channa punctata*). However, to remain consistent with the restrictions under the Lacey Act, the ANSTF decided to expand this plan to include all snakehead species. As information on most snakehead species is lacking, the life histories of only three species are described in this management plan. They include the northern snakehead, giant snakehead, and bullseye snakehead. The goal and objectives of this plan remain applicable to all snakehead species with the assumption that the pathways of introduction and management options are similar for all snakehead species

The goal of this Plan is to use the best available science and management tools to prevent the future introduction of snakehead into new areas, contain and, where possible, eradicate newly established and localized populations, and minimize impacts in areas where they are established and eradication is not feasible. The following objectives set forth by the Plan development committee are necessary to achieve this goal:

1. Prevent importation into the U.S. by refining regulations and improving compliance and enforcement.
2. Contain the expansion of snakehead within the U.S. by assessing the risk of establishment and developing an effective snakehead surveillance program that can detect new introductions at a stage where populations are able to be eradicated.
3. Develop long-term adaptive management options to mitigate potential impacts of snakehead in U.S. waters where eradication is not possible.
4. Conduct research to better understand the pathways of spread and impacts of snakehead on native and beneficial naturalized aquatic organisms, as well as to develop more effective surveillance, control, and eradication methods.
5. Develop effective outreach or education plans and tools to help prevent new introductions of snakehead within the U.S. and control the anthropogenic spread of established populations.
6. Review and assess progress of the Plan.

Biology, Natural History, Ecological and Environmental Impacts of Snakehead

Snakeheads (family Channidae) are air-breathing, freshwater fishes containing two genera, *Channa*, native to Asia, Malaysia, and Indonesia, and *Parachanna*, endemic to tropical Africa. Courtenay and Williams (2004) compiled a document containing summaries of known information for 29 snakehead species. Plan readers are encouraged to view this document for additional information, as this work is cited heavily throughout this Plan. We have supplemented the review by Courtenay and Williams (2004) with additional studies as applicable and have included species that have a high potential to cause negative impacts based on current or historical presence in North America. Most snakeheads have limited colonization potential in the U.S. due to their thermal tolerances (Herborg et al., 2007), with the exception of the northern snakehead. The northern snakehead's native range (24-53°N) and water temperature range (32 - 89°F, 0-31°C) indicates that if introduced, it could establish populations throughout most of the U.S. (Courtenay and Williams, 2004; Herborg et al., 2007); the highest likelihood for colonization may be the mid and northeast Atlantic slope (Poulos et al., 2012). Accordingly, much of the following narrative will be allocated to this species as the existence of several established populations and the species' wide thermal tolerance have ranked the northern snakehead with the highest risk of establishment.

Northern Snakehead (*Channa argus*)

Figure 1. Northern snakehead caught in Virginia. Photo Credit: Steve Chaconas

Northern snakehead is native to rivers and estuaries of China, Russia, and Korea (Courtenay and Williams, 2004). This species was brought from Korea and intentionally

released by culturists in Japan in the early 1900s (Okada, 1960). However, its subsequent release and establishment in ponds, rivers, and reservoirs of present day Kazakhstan, Turkmenistan, and Uzbekistan in the early 1960s may have been accidental via transport in contaminated shipments of Asian carps (Courtenay and Williams, 2004). In many areas of its native (Berg, 1965) and introduced range, northern snakehead is considered a desirable and sought after food fish (Baltz, 1991 as cited in Courtenay and Williams, 2004; Dukravets, 1992; FAO, 1994; Okado, 1960). In China, this species is raised in ponds, rice paddies, and reservoirs (Atkinson, 1977; Sifa and Senlin, 1995 as cited in Courtenay and Williams, 2004; Liu et al., 1998) and is considered the most important snakehead species cultured (Courtenay and Williams, 2004).

In major cities such as Calcutta, Bangkok, Singapore, and Hong Kong, northern snakehead is a specialty food item, available alive in aquaria for customer selection at finer restaurants. They also provide easily caught food for less affluent people (Wee, 1982). Northern snakehead is usually transported alive and killed just prior to preparation. Some Asian cultures, such as in Myanmar, believed that because snakehead can remain alive outside of water for periods of time, the fish have healing properties and are consumed for medicinal purposes (Lee and Ng, 1991). In such situations, the fish are killed just before cooking because of the belief that the healing properties will be lost if the fish are killed sooner (Lee and Ng, 1991).

The northern snakehead is most readily identified by long dorsal and anal fins; pelvic fins located beneath the pectorals; a truncate caudal fin; and, a large mouth extending far beyond the eye with large canine-like teeth on the upper and lower jaws. Adult northern snakehead are golden tan to pale brown or olive in color with a series of dark, irregular patches on the sides and saddle-like blotches across the back interrupted by the dorsal fin. Coloration of juveniles is similar to the adults, which is atypical of most snakehead species (Courtenay and Williams, 2004).

The northern snakehead can grow to at least 33.5 inches (850 mm) total length (TL) (Okada, 1960); however, in Russia there have been reports of captured specimens reaching 4.8 feet (1.5 m) TL (Courtenay and Williams, 2004), while the largest individual documented in Virginia waters was at least as large as 34 inches (864 mm) TL (Odenkirk et al. 2013). Recent evaluations suggested northern snakehead in Potomac River grow faster than previously determined. For example, age-3 fish averaged 14 inches (357 mm) in an early study (Odenkirk and Owens, 2007), which was commensurate with growth rates found in China (Uchida and Fujimoto 1933); however, otolith evaluations and growth of recaptured tagged fish in 2011 implied faster growth. In that study, age-3 fish averaged 25 inches (644 mm), and the resulting growth increment was similar to that of recaptured tagged fish of similar size (Odenkirk et al. 2013). It seems likely northern snakeheads are growing faster in newly colonized North American waters than in waters where the fish is native or has been naturalized for an extensive period. Nonindigenous species may express different life history traits as they adapt to new environments (Jiao et al. 2009), and some fish are known to have elevated degrees of piscivory (relative to body size) when they become established outside their native range (Jang et al. 2006).

Northern snakehead typically reaches sexual maturity at two to three years of age and approximately 11 – 14 inches (300-350 mm) TL but may mature at an earlier age in North America (Odenkirk et al. 2013). Females produce eggs 1 to 5 times per year and release 22,000-51,000 eggs per spawning (Frank, 1970; Nikol'skii, 1956). Dukravets and Machulin (1978) documented fecundity rates that ranged from 28,600-115,000 eggs per spawning for northern snakehead introduced to the Syr Dar'ya basin in Turkmenistan and Uzbekistan. Their eggs float and take approximately 28 hours to hatch at 88°F (31°C) and 45 hours at 77°F (25°C). This evidence demonstrates that the eggs take longer to hatch at lower temperatures. Parents guard the young in a nest until yolk sac absorption is complete at approximately 0.3 inches (8 mm) TL (Uchida and Fujimoto, 1933).

In the lower reaches of the Amu Dar'ya basin of central Asia, Guseva and Zholdasova (1986; as cited by Courtenay and Williams 2004) reported that an accidentally introduced population of northern snakehead fed on crustacean zooplankton and chironomid larvae in their first month of life. At 1.6 inches (40 mm) TL, they began to feed on fish and by 5.1 – 5.9 inches (130-150 mm) fish comprised 64-70 percent of the diet. Juveniles up to 11.8 inches (300 mm) TL fed almost exclusively on fish. Juvenile northern snakehead feed in schools with most of the activity during early evening and again in early morning, usually in vegetation close to shore (Courtenay and Williams, 2004). In addition to fish, adult food items include frogs, crayfish, dragonfly larvae, beetles, and plant material that is probably incidentally ingested along with the prey (Dukravets and Machulin, 1978). According to Odenkirk and Owens (2007), food items observed in the stomachs of 219 northern snakehead collected from the Potomac River between 2004 and 2006 consisted mostly of banded killifish (*Fundulus diaphanous*), white perch (*Morone americana*), bluegill (*Lepomis macrochirus*), and pumpkinseed sunfish (*Lepomis gibbosus*). Saylor et al. (2012) found similar food habits among northern snakehead in the Potomac River with similar fish species consumed most frequently and non-fish taxa consumed rarely. However, crayfish are not uncommonly found in stomachs of northern snakehead in Potomac River (pers. communication, Joseph Love, Maryland Department of Natural Resources). In the Syr Dar'ya basin of central Asia, Dukravets and Machulin (1978) reported that northern snakehead fed on 17 species of fish, including species that measured up to 33 percent of the predator's total body length.

Okado (1960), cited by Courtenay and Williams (2004), reported that the northern snakehead is a voracious feeder. It is an ambush predator that lies on the bottom, waiting for prey (Guseva, 1990). In the Amu Dar'ya basin, northern snakehead only feeds from late March to October with 45.1 percent of its annual food consumption completed by May, another 46.4 percent of annual consumption occurring in June and July, and only 4.6 percent between September and October (Guseva, 1990). No food was found in stomachs during the winter months (Guseva, 1990). Prey items considered valuable as human food fish were common carp (*Cyprinus carpio*), grass carp (*Ctenopharyngodon idella*), bream (*Abramis brama*), zander (*Sander lucioperca*), and catfish (*Ictalurus* spp.) (Guseva, 1990). Where introduced, snakeheads had assumed a predator niche and displaced native pike and catfish in the basin (Guseva, 1990).

Northern snakehead prefers stagnant shallow ponds or swamps with mud substrate and vegetation and slow muddy streams (Okada, 1960), but is also found in canals, reservoirs, lakes, and rivers (Dukravets and Machulin, 1978; Dukravets, 1992). In the Potomac River, northern snakehead is typically found in shallow water with floating and emergent vegetation (Odenkirk and Owens, 2005; Lapointe et al., 2010). The species has a broad temperature range of 32 – 90 °F (0 to 31°C) (Okada, 1960) and may endure water temperatures as high as 104 °F (40°C) without dissolved oxygen (Frank, 1970; Nikol'skii, 1961) or as low as -22 °F (-30°C)(Frank, 1970). The species is an obligate air-breather; therefore, survival in poorly-oxygenated waters is possible (Courtenay and Williams, 2004), though access to the surface is required. Atmospheric oxygen, which is greater in concentration than dissolved oxygen, is absolutely necessary except in the hibernation period when the respiratory function almost ceases (Uchida and Fujimoto, 1933). During cold temperatures, northern snakehead has a reduced metabolism and oxygen demand, which allows them to survive under ice (Frank, 1970).

In 2006, Lapointe et al. (2010) radio-tagged adult northern snakehead in Virginia tributaries of the Potomac to determine seasonal habitat selection. They found that snakehead in the Potomac tributaries generally preferred shallow habitats that provided cover. In the spring (pre-spawning period), snakeheads moved upstream within their respective tributaries and remained there throughout the spawning period. During the spawning season, snakeheads almost exclusively chose habitats along the shoreline that provided macrophyte cover for spawning. During the post-spawn period, from September to November, snakeheads were found in offshore habitats with vegetative cover such as Eurasian milfoil and hydrilla. However, during winter, snakeheads preferred offshore habitats with deep water (Lapointe et al., 2010).

The USFWS and Maryland Department of Natural Resources (MDNR) conducted several experiments at the Joseph Manning Hatchery in Waldorf, Maryland to examine salinity tolerances of northern snakehead. In trials that were conducted at lower temperatures (59 - 68°F, 15-20°C), snakehead exhibited increased tolerance to salinity. However, the upper tolerance level remained at 18 ppt (S. Minkkinen, USFWS, personal communication, 2012). The capture of a snakehead in a pound net in Chesapeake Bay near St. Jerome's Creek, Maryland in May 2010 confirmed northern snakehead's tolerance of elevated salinity (at least temporarily), as surface salinities at the mouth of the Potomac River ranged between 10 and 12 ppt. Snakeheads have also colonized Potomac River tributaries down to the mouth of the river, which required migration through the lower river where salinities typically range from 6-20 ppt. The salt wedge in the lower Potomac River has apparently not prevented the spread of snakehead through the Chesapeake Bay watershed and into neighboring tributaries.

There is little information in the scientific literature about effects of northern snakehead on other aquatic organisms. The predatory nature of northern snakehead suggests their introduction could affect populations of fish, amphibians, and invertebrates through direct predation, competition for food resources, and alteration of food webs (Courtenay and Williams, 2004). The species has a high risk of invasiveness (FISK Score = 28, Copp et al. 2009; pers. communication, J.J. Newhard, USFWS). Through predation, ecosystems

could be affected if northern snakeheads became established in waters with low diversity of native and naturalized fishes and low abundance or absence of other predatory species. These effects could include adversely altering endangered and threatened species populations. Of the taxa listed as endangered and threatened in U.S. aquatic habitats, 16 amphibians, 115 fish, and 5 crustaceans (surface-dwelling crayfish and shrimp), would be the most likely affected (Courtenay and Williams, 2004). Based on habitat requirements and life history of northern snakehead, fish species are most likely to be affected. However, the addition of a predator in the aquatic community could pose a significant threat to any listed amphibian or crustacean species (USFWS, 2002).

The northern snakehead could negatively affect commercially and recreationally important fish populations through predation and competition for food and habitat in ponds, streams, canals, reservoirs, lakes, and rivers. In the Potomac River, northern snakehead have similar habitat and feeding preferences to largemouth bass (*Micropterus salmoides*), but whether a decline in forage availability leads to competition between the two species has yet to be documented (Saylor et. al. 2012). However, Love and Newhard (2012) predicted that if co-occurrence of largemouth bass and northern snakehead increases, then it is possible that largemouth bass abundance may decline in the absence of northern snakehead population control methods. A small established population of northern snakehead in two connected lakes in New York City has remained small and has not affected the relative abundances of coexisting fish populations (Cohen et al. 2012). Thus, while it is difficult to predict the short-term ecological and economic effects of the northern snakehead on recreational and commercial fisheries, methods aimed at restricting size of a population of northern snakehead seem warranted.

Giant Snakehead *(Channa maculata)*

Figure 2. Giant snakehead caught in Wisconsin in 2003. Photo Credit: Wisconsin Department of Natural Resources.

The giant snakehead has been caught in the U.S. and could potentially become established in Florida or Hawaii (Courtenay and Williams, 2004). The native range of the giant snakehead is noncontiguous. It is native to rivers of Southeast Asia in Cambodia, Indonesia, Laos, Malaysia, Thailand, Vietnam, and possibly Myanmar (Courtenay and Williams, 2004). It has also been found in the southwestern region of India, restricted to the Kerala State (Roberts, 1989) as a result of one or more introductions from southeastern Asia that occurred prior to the mid-1800s (Courtenay and Williams, 2004). In its native range it is considered a highly prized food fish with multiple cage culture operations raising giant snakehead for market (Courtenay and Williams, 2004).

This species can grow to 32 inches (1 m) in TL and weigh over 44 pounds (20 kg) (Roberts, 1989; Lee and Ng, 1991; Talwar and Jhingran, 1992, as cited by Courtenay and Williams, 2004). It is believed to be one of the fastest growing snakehead species (Wee 1982; as cited by Courtenay and Williams, 2004).

Giant snakehead reproduction is similar to that of other *channids*. This species removes vegetation in a circular area to spawn. Once spawned, their pelagic eggs rise to the surface and are guarded by parents (Lee and Ng, 1991). Giant snakehead are mainly daytime feeders (Ng and Lim, 1990, cited by Courtenay and Williams, 2004). It is a vicious predator of other fish and is described by several sources of Courtenay and Williams (2004) as being "known to kill more fish than it consumes in its natural habitat." The knife-like shape of their teeth allows prey to be sheared in pieces. This species is primarily piscivorous but does have a diet that includes frogs, birds, and crustaceans (Courtenay and Williams, 2004).

This tropical and subtropical species is extremely limited in where it could potentially establish a viable population in the U.S. Freshwater habitats in southern Florida and Hawaii are likely suitable climates for giant snakehead in the U.S. (Herborg et al., 2007; Courtenay and Williams, 2004). There are no specific temperature requirements in the literature. However, the native range for this species is restricted to southern China, south of the Chang Jiang (Yangtze) basin and Hainan (Nichols, 1943; Okada, 1960; Hay and Hodgkiss, 1981; Uyeno and Arai, 1984); northern Vietnam (Kotellat, 2001a). This species' aggressive nature could allow them to out-compete native and naturalized fish species for food and habitat, posing a serious threat to aquatic ecosystems. The potential impact to the economy could be significant. For example, the Florida fishing industry is estimated as a 2.4 billion dollar per year industry; if the giant snakeheads were to become established, its large size and propensity to kill more fish than it consumes suggest a serious detrimental economic effect to the fishing industry (USFWS 2006).

Bullseye Snakehead (*Channa marulius*)

Figure 3. Bullseye snakehead caught in South Florida. Photo Credit: US Fish and Wildlife Service.

The bullseye snakehead is established in Florida and remains a threat to other southern states. The bullseye snakehead is a freshwater fish with an elongate body shape, very long dorsal and anal fins, a rounded caudal fin, and tubular nostrils. It is native to Pakistan, India, Bangladesh, southern Nepal, Thailand, Myanmar, Laos, Cambodia, and southern China (Courtenay and Williams, 2004). In juvenile fish less than 7.1 inches (180 mm) TL, there is a distinctive orange ocellus near the caudal peduncle (J. Galvez, USFWS, personal communication, 2012; Kottelat, 2001). They have a broadly flattened head, with anteriorly placed eyes, in a dorsolateral position. There is a series of dark blotches along the sides of the body of juvenile fish, which are outlined by a row of white scales. The pectoral fin length is approximately one-half of the head length (Courtenay and Williams, 2004).

Reported to be the largest species in the snakehead family, bullseye snakehead often reach 11.8 inches (300 mm) TL in year one, and a maximum of 47.2 to 48.0 inches (1200 to 1220 mm) TL (Bardach et al. 1972; Talwar and Jhingran, 1992 as cited by Courtenay and Williams, 2004). Maximum sizes have been reported up to 70.9 inches (1800 mm) TL with a weight of 66 lbs (30 kg) in the Maharashtra State of western India (Talwar and Jhingran, 1992 as cited by Courtenay and Williams, 2004). Young bullseye snakeheads are facultative air breathers, whereas this behavior is obligatory among adults. They

prefer sluggish or standing water in rivers, canals, lakes, and swamps that are characterized by submerged aquatic vegetation. Bullseye snakeheads may also occupy areas of flooded forests and deep riverine pools (Courtenay and Williams, 2004). They are often found in deep, clear water with sand or rocky substrate (Talwar and Jhingran, 1992 as cited by Courtenay and Williams, 2004). Thermal preferences are tropical, subtropical, and warm temperate climates (Courtenay and Williams, 2004) with average air temperatures of 75°F to 82°F (24°C to 28°C) (Pethiyagoda, 1991, as cited in Courtenay Williams, 2004). Mean air temperature was identified as the most significant environmental variable with respect to habitat suitability (Herborg et al., 2007), and may explain the more tropical distribution of bullseye snakehead compared to other species of snakehead, such as northern snakehead, in the U.S.

Gut-content analysis of adult bullseye snakehead in West Bengal, India reported stomach contents consisting primarily of fish (40 percent), followed by crustaceans (30 percent), macrophytes (15 percent), larval insects (10 percent), and algae (5 percent) (Dasgupta, 2000). Other dietary analysis of the bullseye snakehead from the River Kali in northern India indicated that more than 60 percent of prey consumed was represented by fish, with the remainder being comprised of crustaceans, gastropods, insects, and larval chironomids (Ahmad et al., 1990).

The bullseye snakehead is an important aquaculture, game, commercial, and aquarium fish (FishBase, 2011). It has been cultured in ponds, rice fields, and other water bodies that do not typically support aquaculture, such as irrigation wells. It is reported that they are highly suitable for cage aquaculture. Because of their aggressive fighting behavior when angled, their popularity as a game species in Thailand may promote intentional introduction into natural water bodies (Courtenay and Williams, 2004). They are a valued species in the live food industry (Herborg et al., 2007) and have been observed as part of the live food fish industry in New York City (L. Smith, personal communication, 2002, in Courtenay and Williams, 2004).

Bullseye snakeheads are known in the aquarium trade as both “giant snakehead” and “cobra snakehead.” Due to U.S. federal legislation prohibiting the importation and transportation of snakehead, it is no longer common in the U.S. aquarium trade. Despite trade restrictions, specimens of bullseye snakehead were found after the ban on importation, indicating that the species can be obtained commercially, albeit illegally (Courtenay and Williams, 2004). Further, discussions within aquarist-oriented online forums have indicated an interest in bullseye snakehead and suggest it may be as popular as the giant snakehead among aquarium enthusiasts (Schmidt, 2001). The discovery of bullseye snakehead in Broward County, Florida, in October 2000, may be the result of an intentional release of an aquarium specimen into a water body (Howells, R.G., Williams, J.D., and Courtenay, W.R., Jr., 2002).

Since their establishment in south Florida in 2000, no negative effects to aquatic species have been attributed to the presence of the bullseye snakehead (K. Gestring, Florida Wildlife Commission, personal communication, 2001). However, it is not unusual for it to take several years for the impact of invasive species to be realized. The invasion of

bullseye snakehead into the U.S. has the potential to negatively affect native and naturalized fish populations, crustaceans, insects, and other aquatic species through predation and competition. Such biological interactions could disrupt existing commercial and recreational fisheries, although with proper marketing, new bullseye recreation and commercial fisheries could be developed.

Regulation of Snakehead in the U.S.

In October 2002, the USFWS listed the family Channidae, which includes the northern snakehead, bullseye snakehead, and giant snakehead, as injurious wildlife under the Lacey Act (18 U.S.C. 42). This listing prohibits the import and interstate transportation of these species. Maximum Title 18 penalties for injurious wildlife violation under the Lacey Act are 6 months in prison and a $5,000 fine for an individual and a $10,000 fine for an organization. Importation and interstate transport may be allowed with a permit for scientific, educational, or zoological purposes (50 CFR 16.22). The USFWS has additional import declaration requirements under 50 CFR 14.61, which requires that all wildlife be declared to the USFWS upon importation. Injurious wildlife listing (Title 18) under the Lacey Act does not regulate intrastate possession, transportation, or sale. However, additional Lacey Act Wildlife Trafficking charges may be filed against individuals and organizations violating State laws prohibiting importing and transporting of snakehead species at the State level under 16 USC 3372. Title 16 violations are a maximum of 5 years in prison and a $250,000 fine for individuals and $500,000 fine for organizations.

To help prevent the introduction and spread of federally listed injurious wildlife, the USFWS and other Federal Agencies have expanded surveillance and enforcement of illegal transportation of federally listed invasive species. The USFWS has acquired a van equipped with x-ray equipment to improve the effectiveness and efficiency of wildlife inspectors' search for invasive species at international ports of entry. In addition, the USFWS works with state partners through domestic interstate investigations to control the spread of invasive species, including snakeheads.

Canada does not have federal regulations prohibiting the import of snakehead but some provincial regulations do prohibit import. Ontario is the only province to ban possession, transportation and sale of live snakeheads. British Columbia and Quebec are the only Canadian provinces that currently import live snakehead for retail and official uses. Currently, there is no legislation preventing the importation of snakehead into Mexico (See the [Tri-national Risk Assessment Guidelines for Aquatic Alien Invasive Species, Test Cases for the Snakehead (Channidae) and Armored Catfishes (Loricariidae) in North American Inland Waters Commission for Environmental Cooperation (CEC) Project Report. April 2009]).

Snakeheads are legally managed to some extent in every state in the U.S. and the regulations are expanded or clarified as new information is obtained. Maine was the first state to enact regulations restricting the importation of exotic wildlife into the state in

1979. Oklahoma was the first state to specifically restrict the importation of snakehead in 1983 and most recently the District of Columbia specifically restricted the possession of snakehead in 2012. Thirteen states as well as the District of Columbia allow harvest of snakehead as long as the fish is immediately killed.

Violations to the state regulations vary greatly from state to state. The minimum fine is $10 (Oklahoma and North Carolina), while the maximum fine charged by a state is $10,000 (Michigan). In Wyoming, violators may lose hunting and fishing privileges in all other Interstate Violators Compact member states for life and be responsible for civil penalties in an amount not to exceed the costs incurred by the commission in removing the illegally stocked fish.

Some states monitor pets shops for illegal sale of snakehead and some states have instituted snakehead buy-back programs. For example, the Nebraska Game and Parks Commission instituted a snakehead buy-back program in 2004 for fish held in private aquaria. One snakehead was purchased through the buy-back program. The Nebraska Game and Parks Commission also initiated undercover visits to both fish markets and the 84 licensed pet shops in the state and found no snakehead in fish markets or pet shops. Nebraska has not had any snakehead incidents since these visits (D. Gabelhouse, Nebraska Game and Parks Commission, personal communication. 2012). For more information on specific state invasive species regulations see these websites: http://www.animallaw.info/articles/ddusinvasives.htm or http://www.invasivespeciesinfo.gov/laws/main.shtml

Introduction of Snakehead into U.S. Waters

Northern snakehead likely arrived in U.S. waters through importation from the live food fish market and to a lesser degree in the aquarium trade. For the last two decades, snakeheads have been imported to the U.S. for sale in ethnic markets and restaurants that hold fish live in aquaria for customer selection. Although the northern snakehead has been the most commonly imported, (Courtenay and Williams, 2004), other snakehead species imported into the U.S. include the blotched, chevron, Chinese, Congo, dwarf, giant, and striped snakeheads. The striped snakehead was a frequent import between 1999 and February 2002 and the dwarf and Congo have been intercepted since the 2002 addition of snakehead to the injurious wildlife list under the Lacey Act (USFWS, 2012).

In 2002, the Channidae family was added to the injurious wildlife list under the Lacey Act. Since this time, the USFWS Office of Law Enforcement has continued to seize illegal shipments of snakehead. As recently as August 2010, 2800 snakehead were seized and destroyed at a New York port and in February 2011 a shipment of over 350 Chinese snakehead were seized at an airport in New York (USFWS, 2011). The Lacey Act does allow permitted access of snakehead for medical, scientific, educational and zoological reasons. Since 2002, seven permits have been issued allowing snakehead into the United States. Five permits were for zoological educational display and two for scientific research within governmental agencies.

Prior to the Lacey Act listing, importation and sale of snakeheads were legal in most states, but prohibited in six states. Some states prohibited possession of only those snakehead species that could become established in their waters. However, even though certain species of snakehead may not be capable of reproducing in some climates, they could be transported to another state where a viable reproducing population could be established. The Lacey Act does not prohibit possession of live snakehead as long as the source of the snakehead is not through interstate or foreign commerce; therefore state laws prohibiting possession of live snakehead are still necessary to allow wildlife law enforcement officers to prove a violation of state or federal law.

Although import records are incomplete and not detailed, it is evident that imports of live snakehead into the U.S. increased from 1997 to 2002 (Table 1) and that China was the biggest exporter of live snakeheads (Table 2). Table 3 shows a decrease in the number of snakeheads imported after the Lacey Act passed in 2002.

Table 1. Importations of live snakehead (Channidae, all species) 1997-2010. Values in italics for years since late 2002 were seized and not allowed into the U.S. (USFWS, 2012)

Year	Number of individuals	Number of Shipments	Total mass (kilograms)	Total declared value (U.S. dollars, individuals and weight combined)
1997	372	--	892	5,085
1998	1,488	--	1,883	12,632
1999	13,059	74	7,645	23,393
2000	8,408	86	9,657	41,087
2001	22,827	90	20,035	41,255
2002	35,324	50	442	46,980
2003	*725*	*3*	--	*445*
2004	*172*	*3*	--	*1,031*
2005	*601*	*4*	--	*4,731*
2006	*0*	*0*	--	*0*
2007	*0*	*0*	--	*0*
2008	*6*	*1*	--	*8*
2009	*276*	*2*	--	*484*
2010	*2,800*	*3*	--	*796*
Totals	86,058	316	40,554	$177,927

Table 2. Origin of snakehead shipments (Channidae, all species) 1997-2010. Number of individuals includes seized shipments (USFWS, 2012)

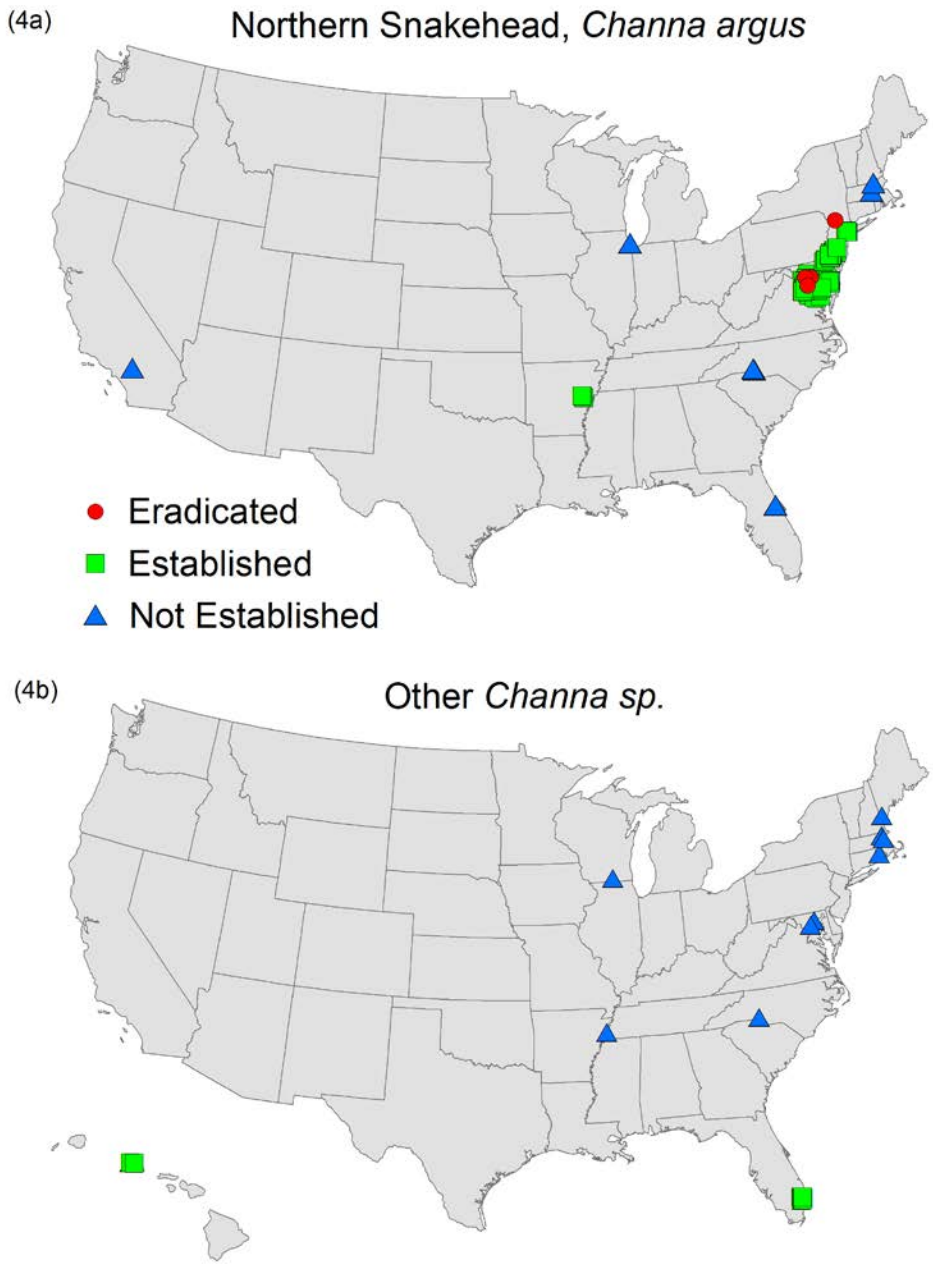
Country	Number of individuals	Total mass (kilograms)	Total declared value (U.S. dollars, individuals and weight combined)
China	68,038	36,784	203,248
Thailand	917	--	4,941
Vietnam	809	995	2,348
India	572	--	1,498
Indonesia	638	--	1,190
Nigeria	1,760	--	949
Macao	2,800	--	796
Congo	250	--	480
Korea	5	--	160
Switzerland	50	--	100
Taiwan	400	--	56
Hong Kong	150	--	24

Table 3. Comparison of live snakehead imported into the U.S. before and after Lacey Act enactment (Channidae, all species) 1999-2010. (USFWS, 2012)

Species	Number before September 2002	Total declared value (U.S. dollars, individuals and weight combined)	Number after September 2002	Total declared value (U.S. dollars, individuals and weight combined)
Species (all)	84,664	175,550	--	--
Striped	2,871	13,692	--	--
Blotched	2,609	4,610	--	--
Chinese	19,394	14,409	2,800	796
Giant	--	--	201	4,379
Northern	--	--	917	1,634
Congo	--	--	250	480
Dwarf	--	--	6	150
Chevron	--	--	6	8

Until the 2002 injurious wildlife listing, the northern snakehead was imported for sale in Asian live food fish markets in Florida, Missouri, New York, and Texas. Live northern snakeheads were also reported in markets in Maryland, Virginia, and Washington D.C. Areas with live food fish markets may have increased the likelihood of creating established snakehead populations in the region. In addition, both the bullseye snakehead population in Florida, established in 2000 (K. Gestring, Florida Wildlife Commission, personal communication, 2001), and the blotched snakehead population in Hawaii, established prior to 1900 (R. Britz, Division of Fishes, National Museum of Natural History, Smithsonian Institution, personal communication, 2002), are believed to be the result of releases from live fish markets. However, northern snakehead has been captured in locations with no indication of a reproducing population. One fish was captured in California in 1997, two in Florida in 2000, one in Illinois in 2004, and two in Massachusetts in 2001 and 2004.

The first report of a northern snakehead in the U.S. mainland was in Silverwood Lake, California, on October 22, 1997, (Figure 7a). The fish was collected by California Department of Fish and Game personnel during electrofishing activities (Courtenay and Williams, 2004). It is unknown how this 27.9 inch (710 mm) specimen was introduced into the lake and no additional fish have been documented in California waters since this incident.



Source: U.S. Geological Survey, September 2013

Figure 4a and 4b. Locations of established northern snakehead, bullseye snakehead, and blotched snakehead populations, the three snakehead species that have known establish populations within the United States. Figure 4a shows locations of established northern snakehead populations (green squares) in the Potomac-Susquehanna-Delaware rivers region. Red circles represent eradicated populations in Catlin Creek, New York, two small water bodies in Crofton and Wheaton, Maryland, and a park pond in the District of Columbia. Figure 4b shows established populations (green squares) of bullseye snakehead in Florida and blotched snakehead in Hawaii. Blue triangles on both U.S. maps represent locations where no more than two fish were collected and have no indication of an established population.

In Florida, two northern snakeheads were caught in the St. Johns River below Lake Harney, Seminole, and Volusia counties in 2000, with unconfirmed reports of an additional three individuals caught nearby. Reproduction and establishment in this area has not been confirmed. The fish may have been intentionally introduced from the live food fish trade to establish a local source of fish, even though possession of the species in that state was illegal (Courtenay and Williams, 2004).

In May 2002, the first known established population in the U.S. was discovered within a small pond in Crofton, Maryland when an 18 inch (457.2 mm) northern snakehead was caught by an angler (Figure 5). The angler took several pictures of the fish and then released it back in the pond. After examining the pictures, MDNR identified the fish as a northern snakehead and this was later confirmed by an expert. On June 30, 2002, another angler caught a 26 inch (660.4 mm) northern snakehead and soon after collected eight juvenile snakehead. Using electrofishing to investigate the invasion, MDNR personnel captured more than 100 young-of-the-year snakehead which were positively identified as northern snakehead. In September 2002, the pond was treated with rotenone, a fish toxicant, to eradicate the established population. During the eradication effort, over 1200 snakehead were recovered. MDNR police determined the source of the introduction as a local resident who purchased three fish at a live food fish market in New York in 2000 and shortly after released the fish into the Crofton pond (Boesch, 2002).

In July 2002, two North Carolina anglers reported catching two northern snakehead from Lake Wylie, a reservoir of the Catawba River. The following month, North Carolina Wildlife Resources Commission (NCWRC) personnel sampled the lake by electrofishing, but failed to recover any snakehead (Courtenay and Williams, 2004). However, in 2007 another northern snakehead was caught by anglers in the same reservoir and a blotched snakehead was caught in 2009.

In May 2004, northern snakeheads of multiple year classes were collected within a 14 mile (23 km) reach of the tidal freshwater Potomac River in Virginia and Maryland downstream of Washington, D.C., indicating a self-sustaining population. Genetic analysis of a subset of fish from 2004 suggested most were offspring of either a single pair of breeding adults or multiple female siblings that had been deliberately or unintentionally released (Orrell and Weigt, 2005). Ten of the original 20 fish collected during 2004 were collected from Dogue Creek (Figure 5), and multiple collections occurred in adjacent creeks both to the north and south of Dogue Creek suggesting an epicenter or point of introduction. By the end of 2010, the population had expanded rapidly in range and abundance inhabiting the main stem and all tributaries of the Potomac River from Great Falls down to the river mouth. While northern snakehead was occasionally found in the main stem of the Potomac River, they were more abundant in shallower tributaries.

In July 2004, an angler caught and preserved two snakehead from Meadow Lake, a 17 acre (6.9 hectare) park lake in Philadelphia, Pennsylvania (Figure 5). The fish were later identified as northern snakehead and a total of six were captured from the lake. In 2005,

sampling efforts resulted in the capture of several size-classes of snakehead, including juveniles (R. Horwitz, Pennsylvania Academy of Natural Sciences, personal communication). Meadow Lake is part of a maze of interconnected embayments and tidal sloughs. Given the openness of the system, Pennsylvania Fish and Boat Commission (PFBC) biologists concluded that the fish had probably accessed adjoining waters of the nearby lower Schuylkill and Delaware rivers. As a result, PFBC biologists decided that they would monitor the pond and surrounding waters but eradication would not be feasible (PFBC press release, July 23, 2004). Since that time, there have been confirmed reports of snakehead in Pennsylvania from the Schuylkill River as well as from New Jersey within the Delaware River and its tributaries.

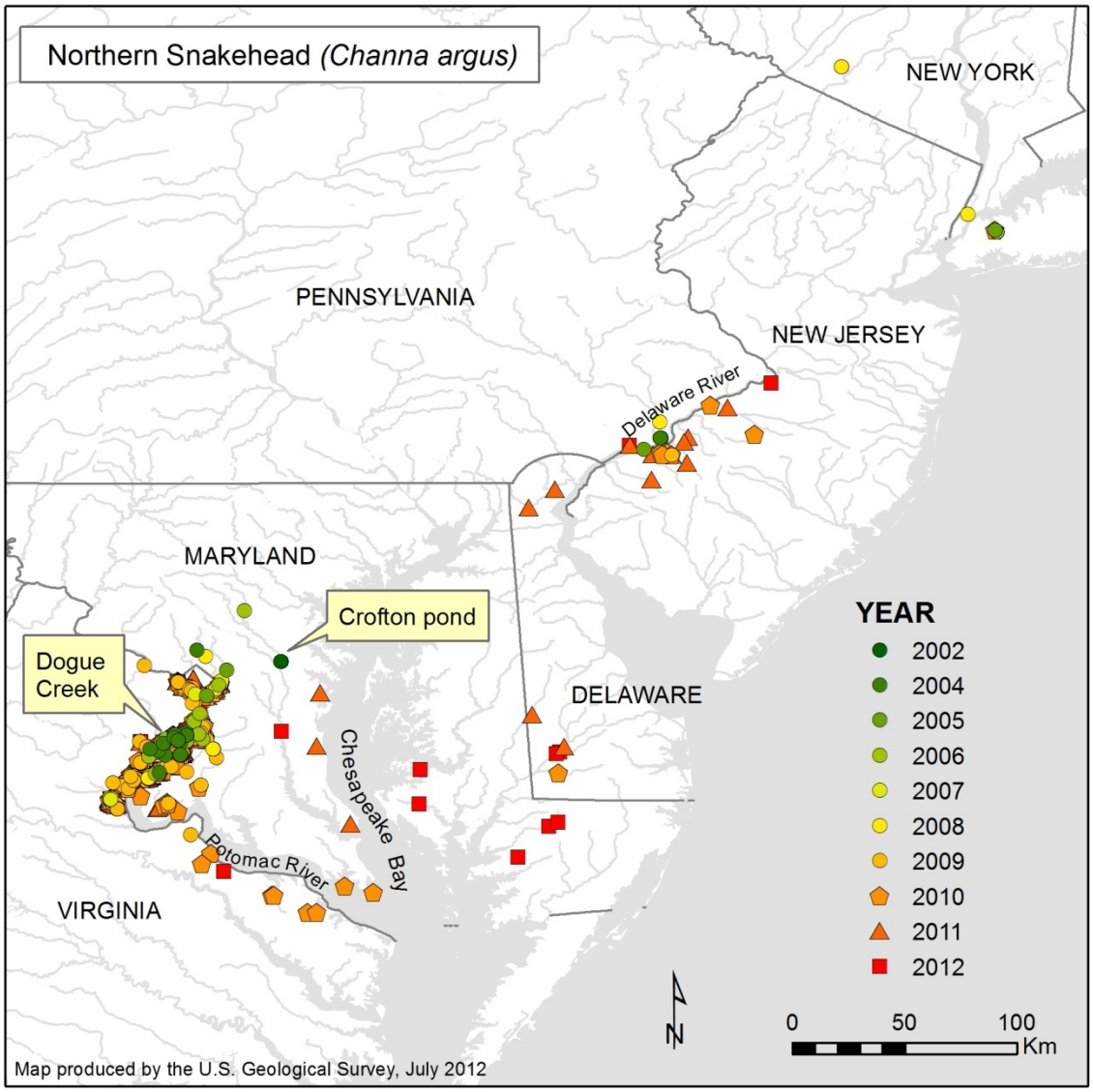


Figure 5. Locations of northern snakehead collections and observations in the Mid-Atlantic region of the U.S. Crofton pond in Maryland was the first documented location of northern snakehead in the region. Dogue Creek in Virginia is believed to be the point of introduction of the Potomac River population, July 2012.

In 2005, four northern snakeheads were found in two park ponds in Queens, New York (Figure 5). These ponds likely have established populations of northern snakehead, yet they have been contained to prevent invasion to other waterways. In July, 2012 DEC Fisheries observed northern snakeheads in a canal of 12 ppt salinity, located across brackish Flushing Creek, from Meadow Lake in College Point, Queens. Six northern snakeheads, ranging from 17 to 23 inches (431.9 to 584.2 mm), were caught in one hour of angling from the Flushing Airport drainage basin which is a freshwater wetland system and connected to the aforementioned canal, confirming the presence of a population of northern snakeheads in College Point, Queens (L. Surprenant, NYDEC, personal communication, 2013). The population in Meadow Lake was likely a result of repeated introductions (King and Johnson 2011).

About fifty miles to the northwest in Orange County, New York, additional northern snakeheads were found in May 2008 in Ridgebury Lake (Figure 5), which is part of the Wallkill River drainage, a tributary to the Hudson River. In August 2008, Ridgebury Lake, Catlin Creek, and adjacent ponds downstream were treated with rotenone. More than 200 northern snakeheads were recovered following treatment and almost all were juveniles, suggesting that the species was successfully reproducing. Two adults were caught in Valentine's Pond, downstream from Ridgebury Lake in 2009, and the system was retreated in the fall of 2009. Subsequent monitoring has failed to detect any snakeheads in the areas treated or downstream in the watershed. This population is thought to have been eradicated and in 2013 the New York Department of Environmental Conservation (NYDEC), the Nature Conservancy, and Central Michigan University took 275 water samples from this watershed to test for Northern Snakehead environmental DNA (eDNA). Results from this sampling should become available in early 2014 (L. Wilson, NYDEC, personal communication, 2012).

In June 2010, a northern snakehead was captured in the Chesapeake Bay near St. Jerome's Creek, (Figure 5), which is near the mouth of the Potomac River in Maryland. Another northern snakehead was caught in the same creek on May 4, 2011. Colonization of downstream tributaries in the Chesapeake suggests that greater salinities of the lower Chesapeake Bay have not deterred movement and natural range expansion of northern snakehead. Cascading water at Great Falls presumably blocks upstream movement of snakehead in the Potomac, but there is concern that the adjacent C&O Canal could allow fish to bypass the falls. However, to date, northern snakehead has not been collected in any of the occasionally dewatered canals. During the summer 2012, four northern snakeheads were caught by anglers in the upper Rappahannock River drainage (Massaponax Creek, VA; personal communication, J. Odenkirk, Virginia Division of Game and Inland Fisheries), which neighbors Potomac River to the south. The pathway of introduction to Rappahannock River is unclear. However, northern snakehead has seemingly spread naturally to Patuxent River (MD), which also neighbors Potomac River. Additionally, a northern snakehead was photographed on near shore, sandy substrate (salinity ~ 12) between the mouths of Potomac River and Rappahannock River in 2013. Thus, natural expansion of northern snakehead into neighboring rivers of Potomac River is occurring.

Northern snakeheads have been collected from elsewhere in the Chesapeake Bay watershed. In October 2010, a large northern snakehead was collected by Delaware Department of Natural Resources (DDNR) biologists in Broad Creek (Nanticoke River watershed; Figure 5) during an electrofishing survey. The fish was found in shallow waters at the mouth of the stream coming from Horseys Pond. Subsequent sampling in Broad Creek and in Horseys Pond failed to find additional snakehead. However, at least eight fish have been collected from Delaware portions of the Nanticoke River from 2010 to 2012. In 2011, northern snakehead was reported from Marshyhope Creek, a tributary of Nanticoke River. From there, it is likely the species spread from the mouth of Nanticoke River into the neighboring Wicomico River and Blackwater River. During spring 2012, multiple fish were caught in the Wicomico River near Salisbury. Additionally, the species was caught by anglers on a footbridge in Blackwater River located on Blackwater National Wildlife Refuge. Shortly thereafter, northern snakehead was caught on Little Choptank River, which is confluent with Blackwater River. In 2013, young northern snakeheads were caught in small ditches that join the upper Blackwater River with the lower Choptank River. It is likely that upper Choptank River will be colonized in the near future (personal communication, J. Love, MDNR Inland Fisheries). Northern snakehead has also been reported from elsewhere in Delaware. In 2011, two snakeheads guarding a nest were reported from Becks Pond and another was caught in Nonesuch Creek, a tributary to the Christina River (Delaware Bay watershed) in New Castle.

The species has been sporadically collected in other areas of the Chesapeake Bay watershed, including Rhode River (2012) and Patapsco River (2014). These incidental collections may reflect long distance movements of northern snakehead from Potomac River or Patuxent River. Northern snakeheads are capable of traveling the length of the Potomac River within a single season (unpubl. data, J. Newhard, USFWS) and may likewise travel long distances in the Chesapeake Bay. Because the species is attracted to freshwater flow during spring, it is possible individuals navigate toward the head of the Chesapeake Bay, the largest freshwater drainage of the Bay (i.e., Susquehanna River). The collections may also represent intentional releases. In either case, reproducing populations for Rhode River and Patapsco River have not been documented.

In Arkansas, one fish farm cultured northern snakehead until importation, culture, sale, and possession of snakehead were prohibited by the Arkansas Game and Fish Commission (AGFC) in August 2002 (M. Freeze, AGFC, personal communication, 2004) and the Lacey Act in October 2002. However, in 2008, the AGFC discovered a population of northern snakehead in the Big Piney Creek watershed (Figure 7a) that likely escaped from farm ponds. This invasion was of particularly high concern as Big Piney Creek is part of the White River system in Arkansas, a tributary of the Mississippi River. An attempt was made to eradicate the Piney Creek population by applying rotenone to 50,021 acres (20,234 hectares) of the watershed. The massive eradication attempt was unsuccessful as live northern snakeheads were found during post-monitoring efforts. Currently, northern snakeheads still inhabit the Big Piney Creek watershed and several have been found outside of this watershed. Widespread flooding events during 2009 to 2011 resulted in further lateral and downstream spread. Extensive delimitation

surveys are required to determine the full extent of this population. Preliminary trials are underway to test the efficacy of eDNA detection methods, as this approach may enable large areas to be surveyed rapidly and with greater detection sensitivity than traditional fisheries tools (Jerde et al., 2011, L. Holt, AGFC, personal communication, 2012). AGFC is still considering the feasibility and practicality of using chemical treatments to control the spread of northern snakehead; however, new labeling protocols have greatly slowed and restricted their control efforts.

Potential for the Spread of Snakehead in U.S. Waters

Snakeheads may be introduced to watersheds via intentional or unintentional release of captive fish or by natural dispersal of fish from established populations in interconnected watersheds. Although importation and interstate transport of snakehead have been prohibited under the Lacey Act since October 4, 2002, live snakehead imports continue to be seized as recently as February 2010 by USFWS agents. In addition, snakeheads may be intentionally released into the environment when they are no longer wanted as pets or as part of a religious ceremony (Severinghaus and Chi, 1999). In an East Asian practice called "prayer animal release" or "ceremonial animal release," people free captive animals into the wild, believing that one gains merit with the gods by doing so. Prayer animals are supplied mainly by pet stores, which obtain them from dealers or trappers.

The desire for wider availability of live snakehead within the food fish market to aquarium trade could potentially increase the probability of introductions (Courtenay and Williams, 2004). Another probable source of spread is created by anglers, who may introduce these fish into new waters to create sportfishing opportunities (Courtenay and Williams, 2004). Concerns of species spread are heightened by the fact that these species are obligate air-breathers and can be easily transported alive out of water as long as they are kept moist (Courtenay and Williams, 2004). Further, as shown by the northern snakehead invasion in Crofton, Maryland, it is evident populations can establish even when propagule pressure (number of individuals of a species released into an area) is low.

In the Potomac River, one haplotype was shared by 15 fish less than 480 mm TL indicating these fish were progeny of either a single breeding pair or the offspring from multiple adult female siblings (Orrell and Weigt, 2005). Multiple, repeated introductions of northern snakehead to Potomac River may have occurred. Orrell and Weight (2005) further noted that mitochondrial sequence variation indicated that introductions to Potomac River tributaries, Crofton Pond and Pine Lake in Maryland, Newton Pond in Massachusetts, and FDR Park in Pennsylvania were separate and no two introductions came from the same source.

Determining the current location of all snakehead occurrences would help contain populations and prevent further spread of snakehead. Uncertainty still appears to exist over the status of sites where single or small numbers of individual fish have been collected, namely California, Florida, Illinois, and Massachusetts, North Carolina. Only

eight fish across the five states have been collected since 1997. Subsequent sampling and monitoring after each collection has led to no further specimens. Surveys have relied upon traditional sampling methods that may have low detection sensitivity, thus earlier efforts may have failed to detect rare fish in the earliest phases of establishment. However, the lack of reported specimens from anglers supports the notion that snakehead populations remain unestablished in these waters. Areas where snakeheads have been previously reported should continue to be carefully monitored and rapidly contained if new individuals are detected. If not responded to in a rapid manner, new introductions may quickly spread and lead to established populations. For example, if snakeheads were to become established in waterways in the Chicago area, then they may have the potential to invade the upper Mississippi River drainage and Great Lakes. Monitoring techniques may improve as new eDNA detection tools (Jerde et al., 2011; Ficetola et al., 2008) continue to develop.

Forecasting Future Invasion of Snakehead in U.S. Waters

Predicting future biological invasions is an important component for control and management plans. However, forecasting the spread and establishment of non-native species remains difficult as a broad spectrum of physiological tolerances, species interactions, and anthropogenic influences must be considered. Many risk assessment methods examine environmental conditions to identify potential habitat where a species may successfully establish, although such species distribution models often vary among the variables and algorithms used (e.g., Carpenter et al. 1993, Stockwell 1999, Scholkopf et al. 2001, Anderson et al. 2003, Phillips et al. 2006, Bomford 2008). The USFWS is currently exploring the applications of the Risk Assessment and Mapping Program (RAMP), an experimental modeling technique used to identify areas within the continental U.S. where a non-native species may successfully establish. Following Climatch, an Australian exotic vertebrate risk assessment model (Bomford 2008), RAMP uses 16 climate parameters (climate and rainfall variables, Table 4) collected from global meteorological stations. Euclidian Algorithms are used to compare data from the continental U.S. to that from the native range of the target species to estimate the extent of areas that are climatically similar.

Table 4. Climate parameters used for RAMP risk assessments

Temperature parameters (°C)	Rainfall parameters (mm)
Annual Mean Temperature	Annual Precipitation
Maximum of Warmest Month	Mean of Wettest Month
Minimum of Coldest Month	Mean of Driest Month
Annual Range	Mean Seasonality (Coefficient of Variation)
Mean of Wettest Quarter	Mean of Wettest Quarter
Mean of Driest Quarter	Mean of Driest Quarter

Mean of Warmest Quarter	Mean of Warmest Quarter
Mean of Coldest Quarter	Mean of Coldest Quarter

Environmental similarities are often presumed to facilitate biological invasion (Moyle 1986, Brown 1989); nevertheless, climatic matching provides only broad parameters for determining habitat suitability. Temperature has been shown to play a key role in snakehead survival (Herborg et. al. 2007); however, many other factors may influence establishment including water chemistry, flow dynamics, resource availability, and the presence of competitors, predators, or disease (Bomford 2008). For example, in the case of the northern snakehead, Poulos et. al. (2012) suggested that elevation may be a better predictor for invasion as low elevation, slow-flowing waters with emergent vegetation support the life history requirements of the species. Detailed information is lacking for most snakehead species, thus restricting the development of more complex models. More sophisticated algorithms may perform better, yet climate matching tools provide simple, repeatable results that are an important consideration when predicting whether an introduced species will become established.

For this management plan, RAMP was used to generate climate match models for the 10 high profile snakehead species identified in Herboug et. al. 2007 as well as three others that were considered to be at high risk for introduction based on data from the USFWS Law Enforcement Management Information System (LEMIS). These additional species are the Congo (*Parachanna insignis*), dwarf (*Channa gachua*), and striped (*Ophicephalus striatus*). The striped snakehead was frequently imported between 1999 and February 2002 and the Congo and dwarf snakeheads were both intercepted at U. S. ports after snakehead were added to the injurious wildlife list under the Lacey Act (USFWS 2012). These maps are included in this Plan to encourage management towards prevention and containment. By showing the risk of spread and establishment, appropriate risk management actions by states (including prohibiting use, sale, or possession) and industry (restricting trade in high risk areas) can be supported. Federal prohibitions for snakehead species prevent importation and interstate transport; however, risk assessment is a critical next step since legal possession, sale, and intrastate commerce may continue to occur as evidenced by importation records both prior to and after their listing as injurious wildlife (Table 3).

The RAMP maps predict a wide range of suitable habitat across the continental U.S. for the northern snakehead. Other species (giant, bullseye, blotched, chevron, Chinese, Congo, dwarf, spotted, and stripped) demonstrated high suitability only to climates in the southern U.S. The golden, Niger, and rainbow snakehead are predicted to have low climate environmental suitability in all U.S. continental areas except for the most southern areas in Florida. Other risk assessment tools, using different parameters, may produce varied projections of distribution. The RAMP assessment method developed by USFWS will continue to be reviewed and tested; however, research managers are encouraged to also consider the results from alternative analyses (e.g., Herborg et. al. 2007, Poulos et. al. 2012). Different methodologies may produce many similar

predictions, yet there will also be notable differences. For example, Herborg et. al. 2007 predicts that the rainbow snakehead will have a wide range of suitable habitat across North America, whereas the RAMP results suggest low suitability for all areas except southern Florida. In the case of the northern snakehead, the environmental similarities projected by RAMP indicate high suitability for the state of Florida, yet Herborg et. al. (2007) concludes that most of the state's climate is unsuitable for survival. These differences illustrate the level of expected uncertainty with the use of any modeling tool. Projections demonstrating uncertainty may be used to further explore the risk to appropriately inform prevention, early detection monitoring, and other risk management actions.

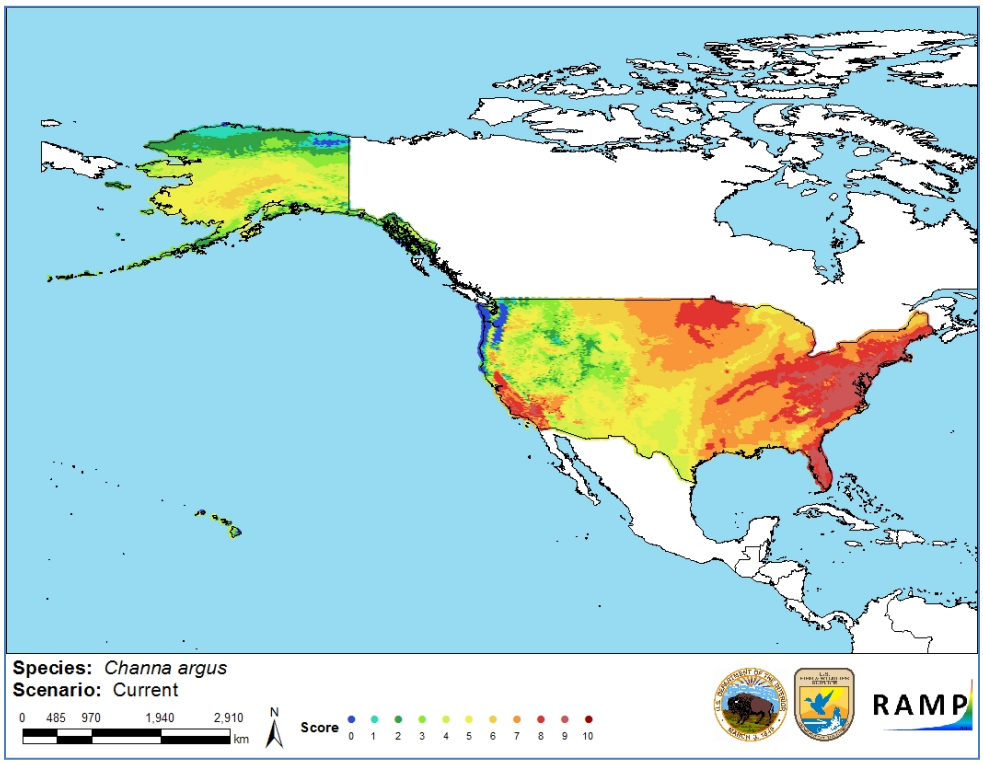


Figure 6. RAMP Result for Northern snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

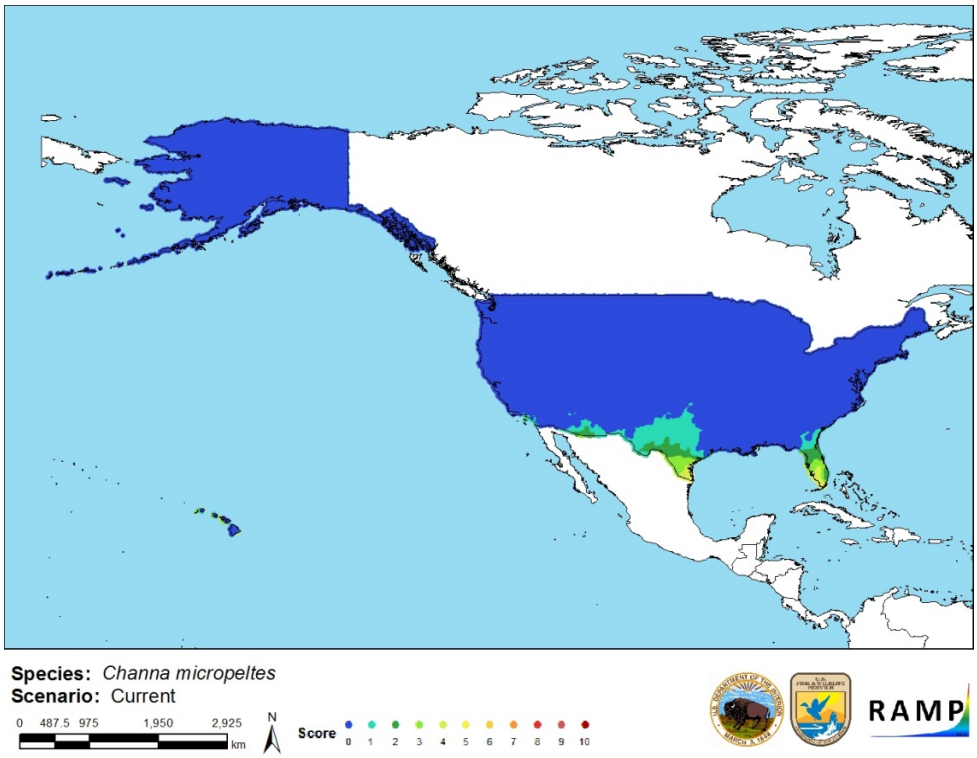


Figure 7. RAMP Result for giant snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

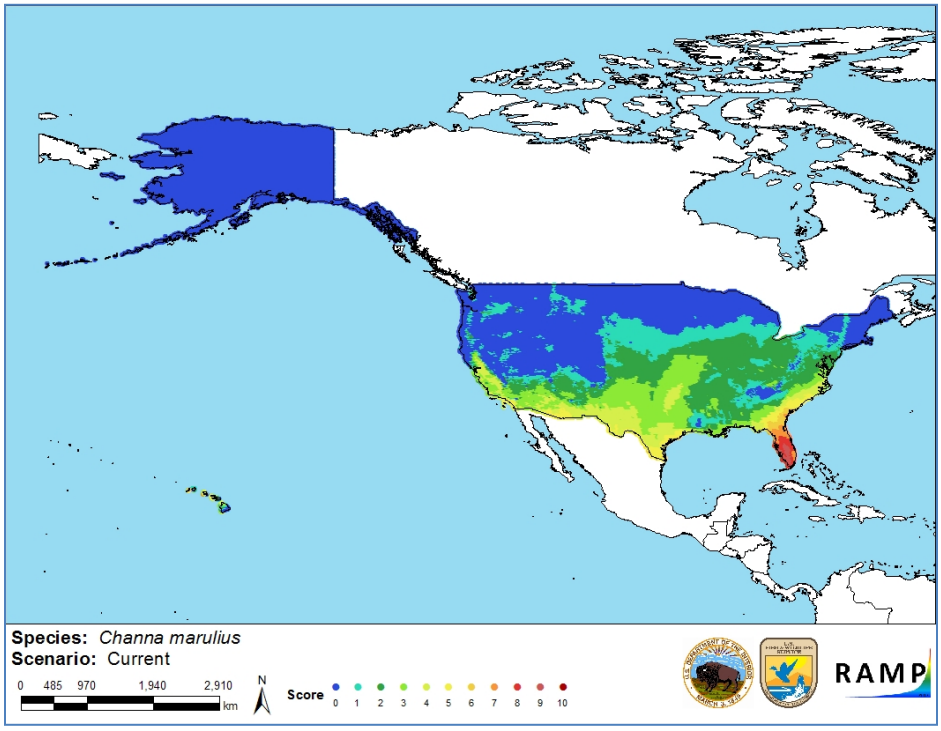


Figure 8. RAMP Result for bullseye snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

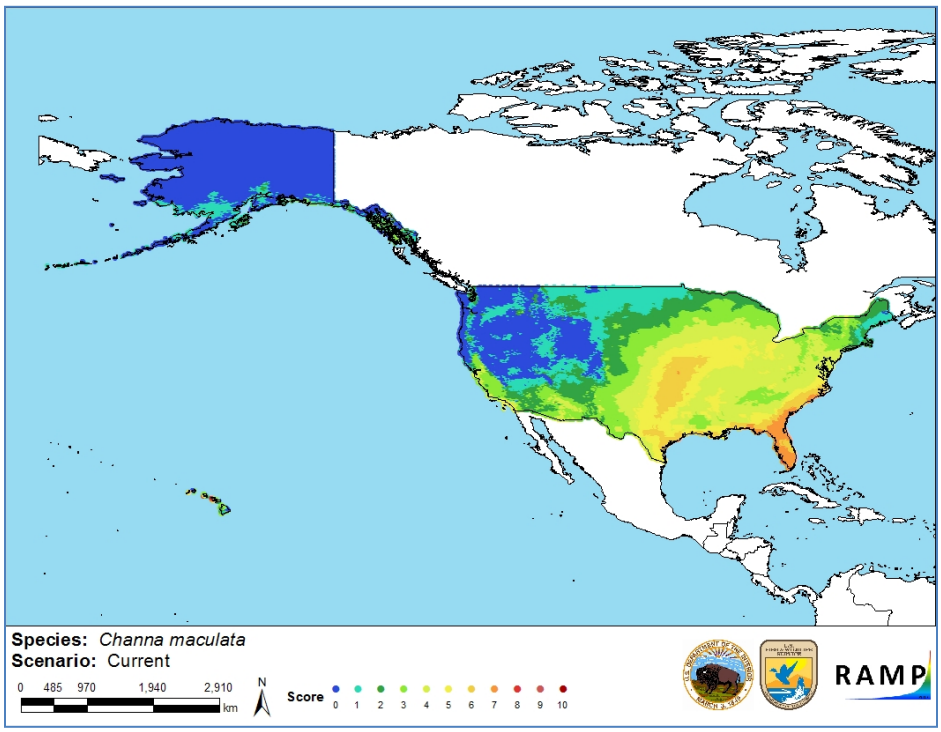


Figure 9. RAMP Result for blotched snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

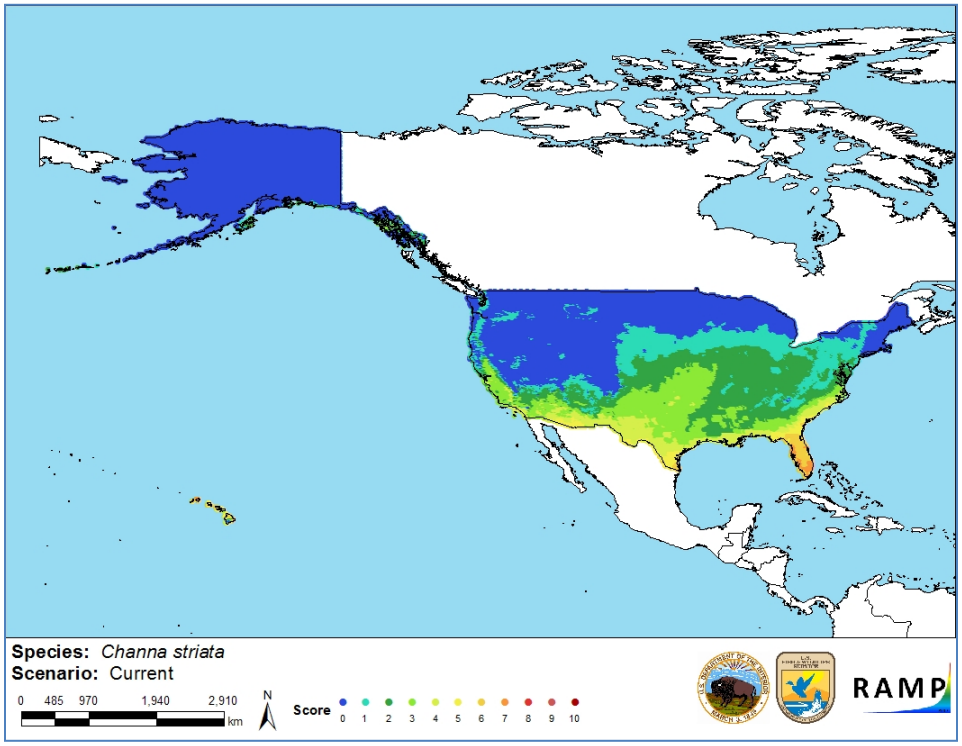


Figure 10. RAMP Result for chevron snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

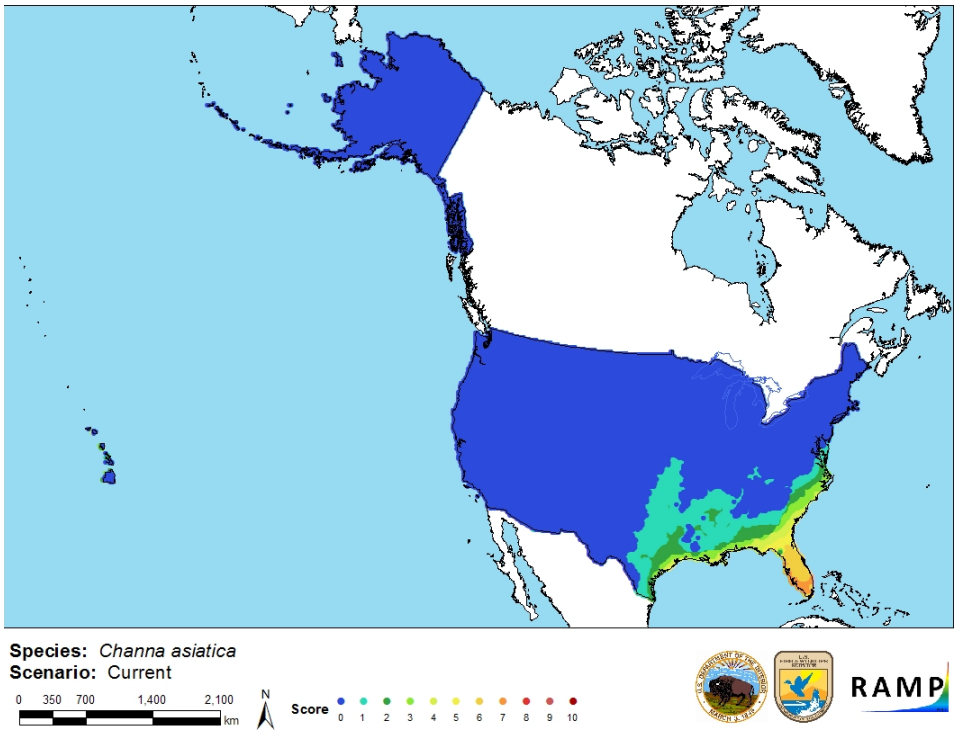


Figure 11. RAMP Result for Chinese snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

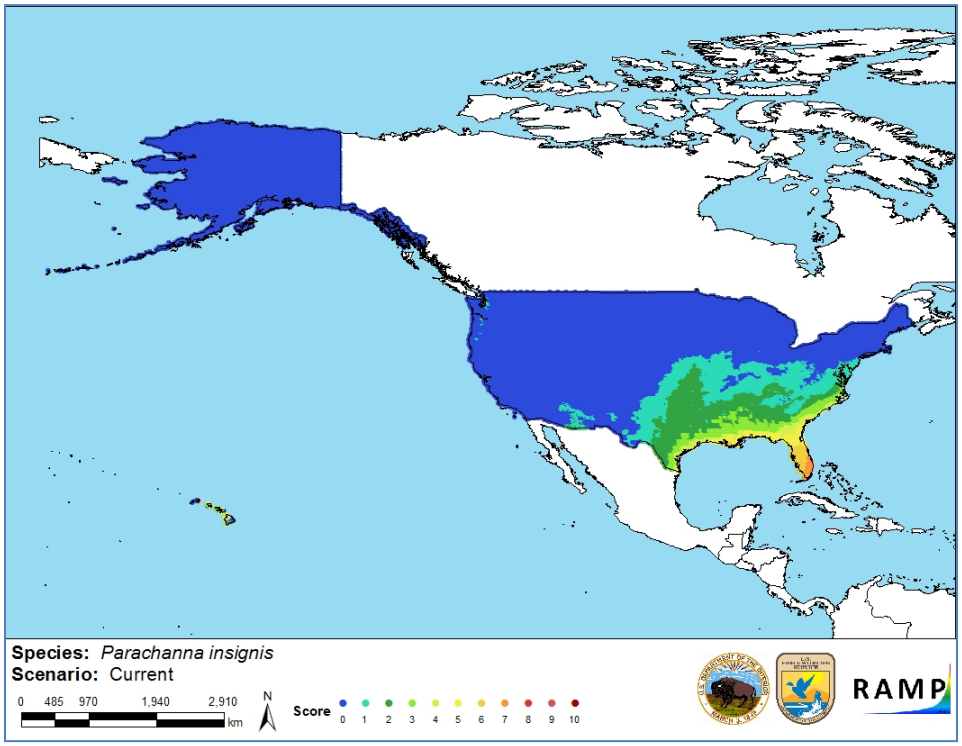


Figure 12. RAMP Result for Congo snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

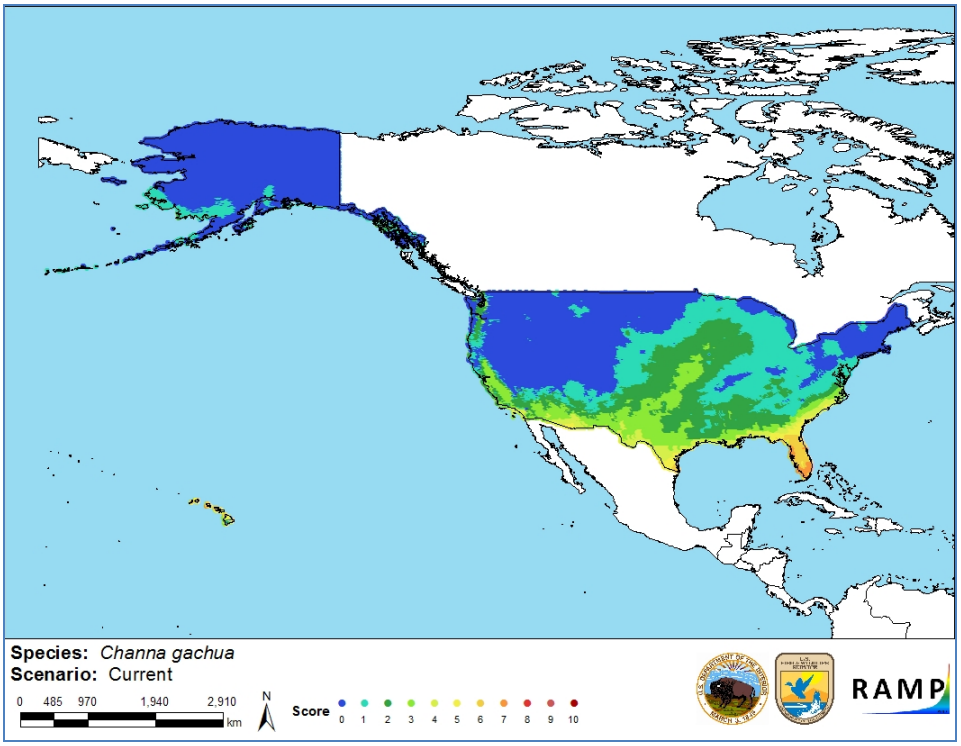


Figure 13. RAMP Result for dwarf snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

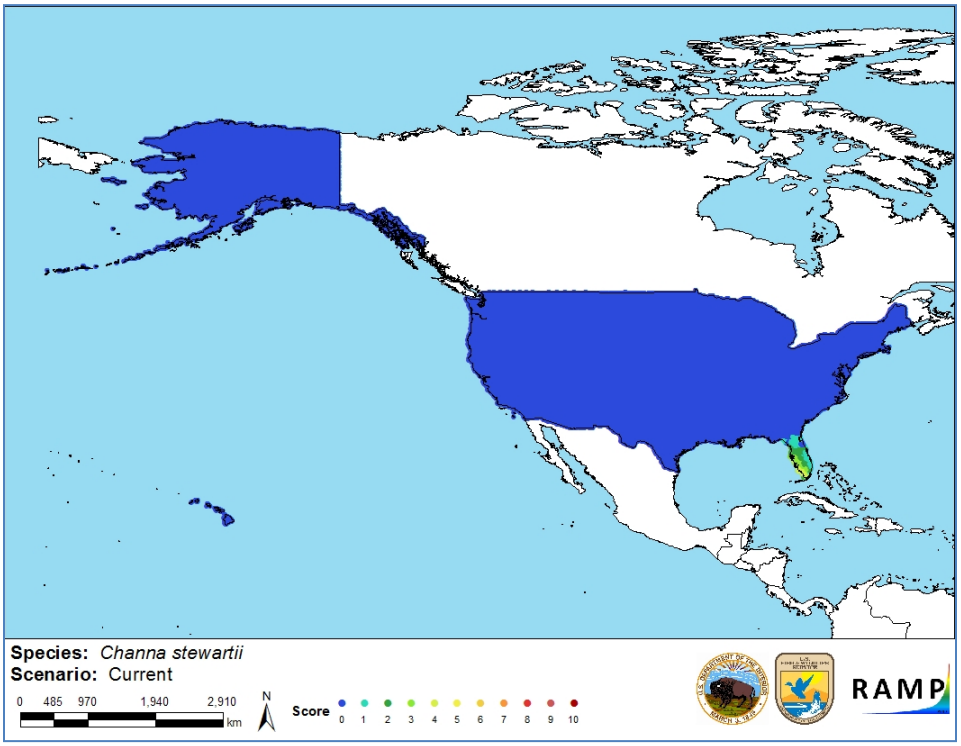


Figure 14. RAMP Result for golden snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

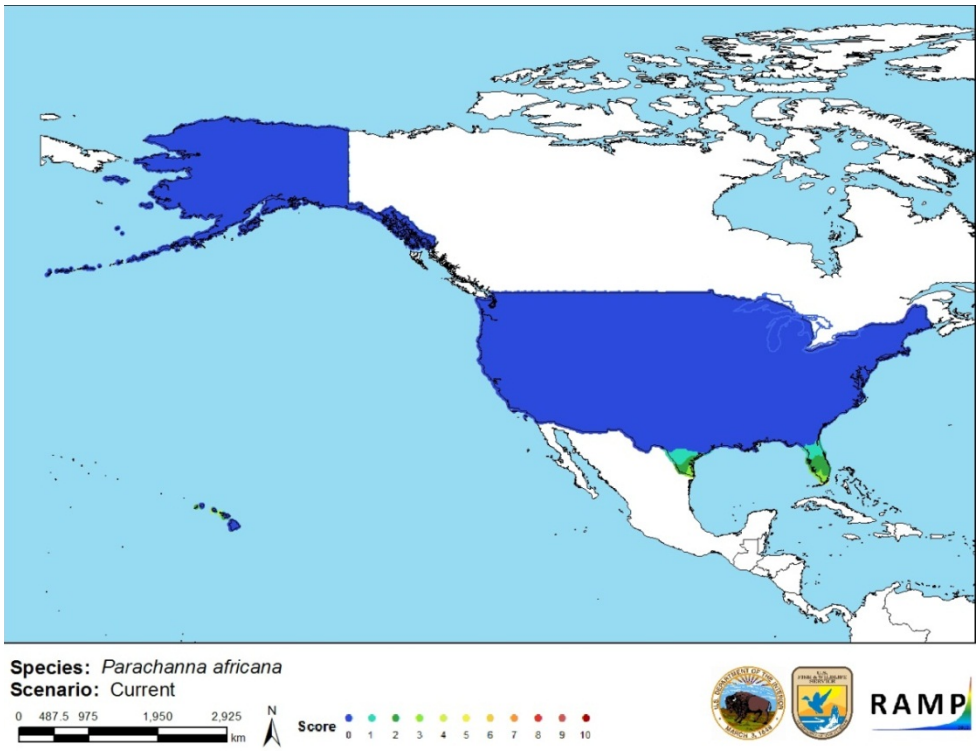


Figure 15. RAMP Result for Niger snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

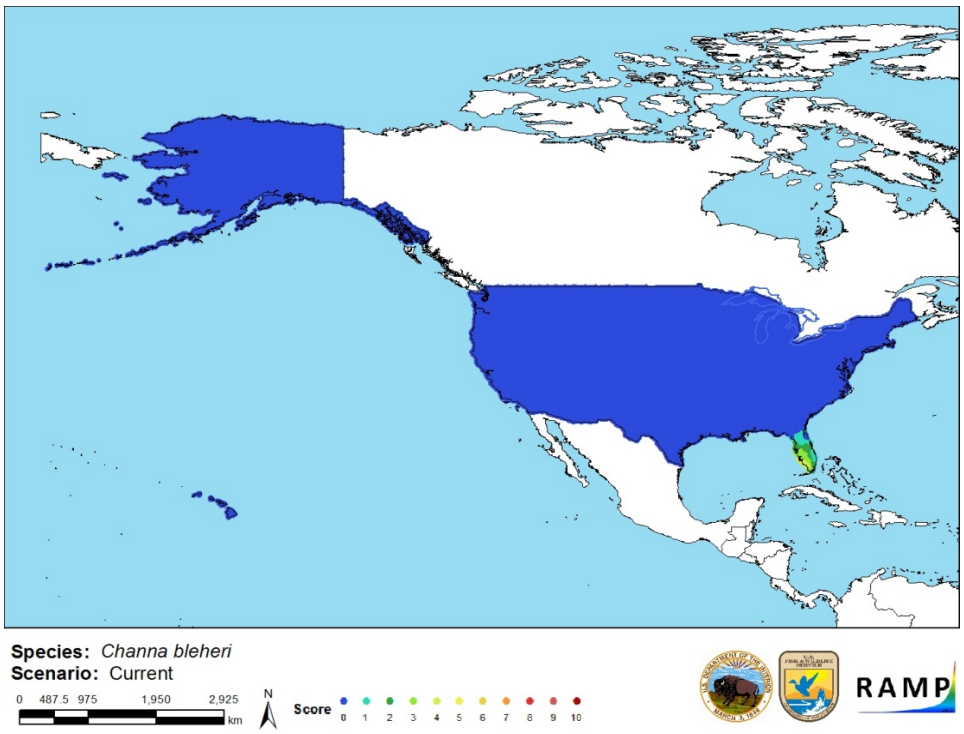


Figure 16. RAMP Result for rainbow snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

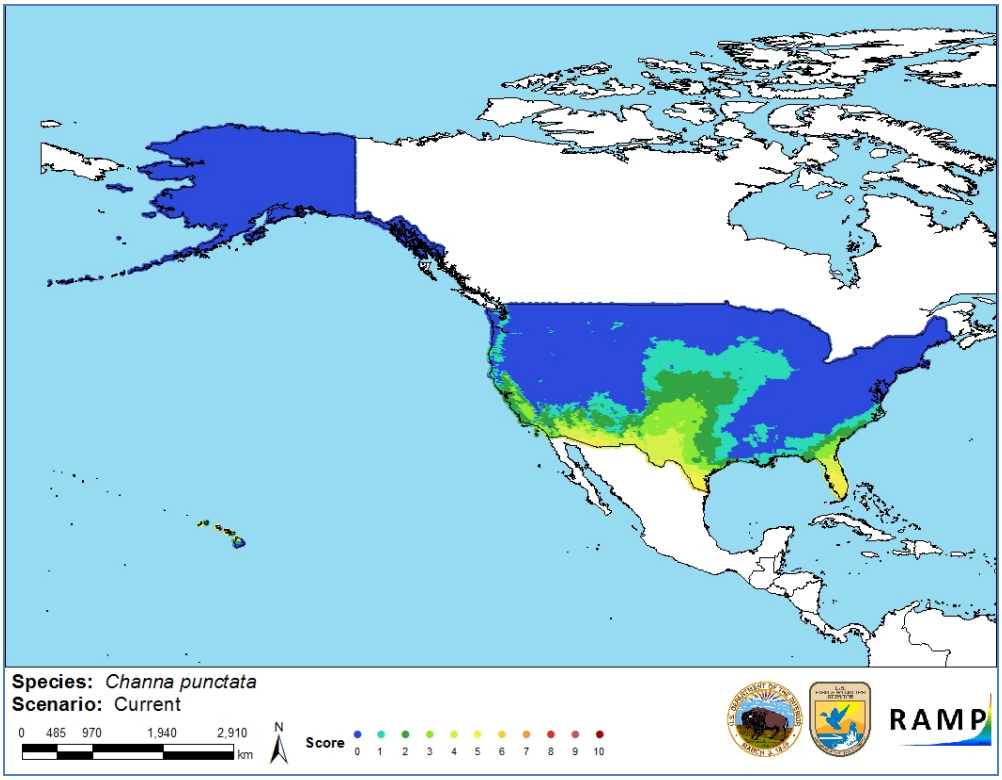


Figure 17. RAMP Result for spotted snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

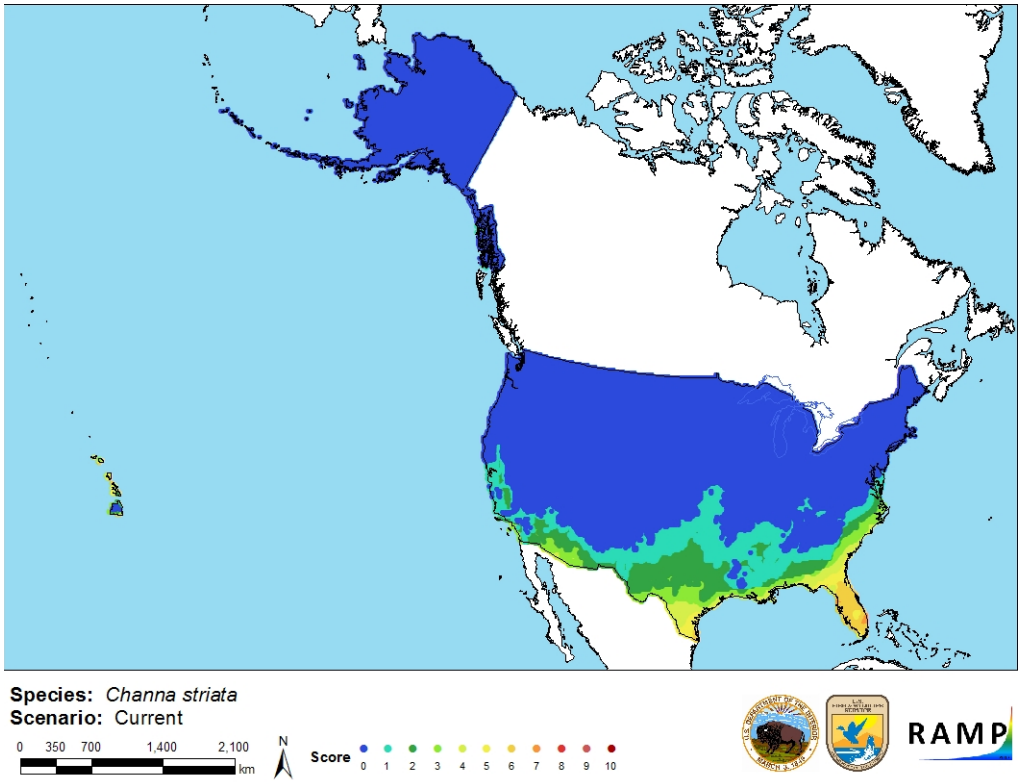


Figure 18. RAMP Result for striped snakehead. (Higher degrees of climate match are warmer colors which represent scores from 5-10.)

Forecasting Range Expansion of Snakehead in U.S. Waters

Connectivity of waterbodies was used in combination with the RAMP results to demonstrate where a snakehead species could potentially expand its current range. These Clima-Con maps were constructed by identifying watersheds that are connected (without barriers) to a known invasion site. If one watershed contains a successful invasion all of the watersheds within the river system are considered connected. The following RAMP data was averaged for each watershed. If the average RAMP score was above 5.5 (out of 10), the watershed was considered to have a climate suitable for survival. Using these methods, Clima-con maps (Figures 19 and 20) were produced for the two species of snakehead that are established in the continental U.S: the northern and bullseye. By combining connectivity and climate suitability, the Clima-Con maps project areas where a species could expand its invaded range via connected waterways.

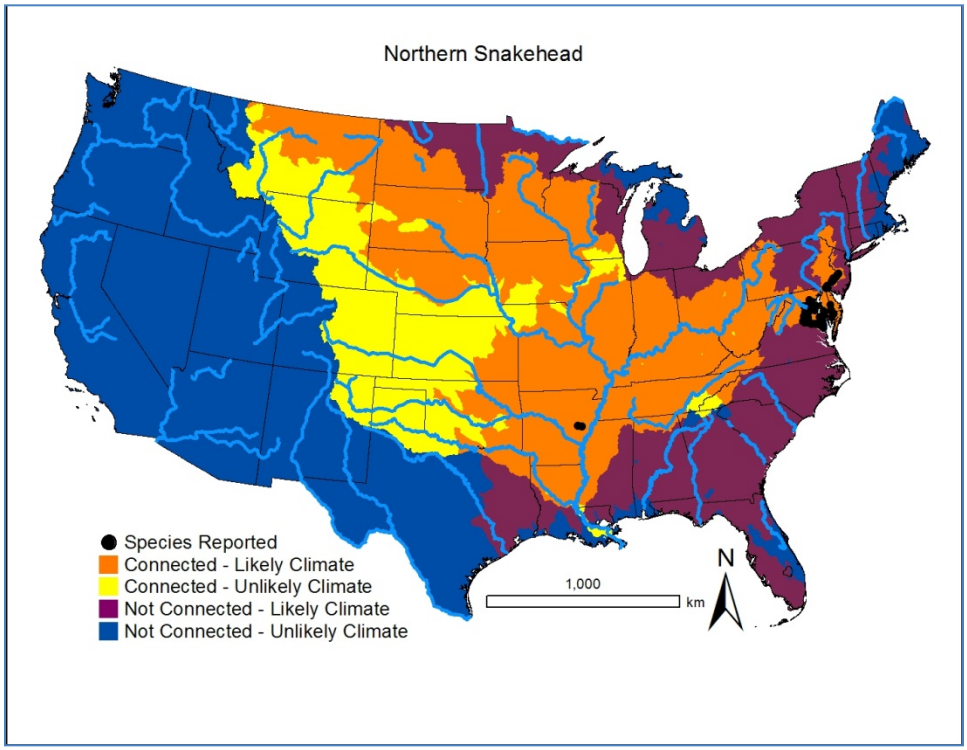


Figure 19. Nationally Prioritized Clima-Con Maps for Northern Snakehead. Connected shows areas where snakehead is present and could invade via connected waterways. Not connected shows connected waterways where snakehead is currently not present.

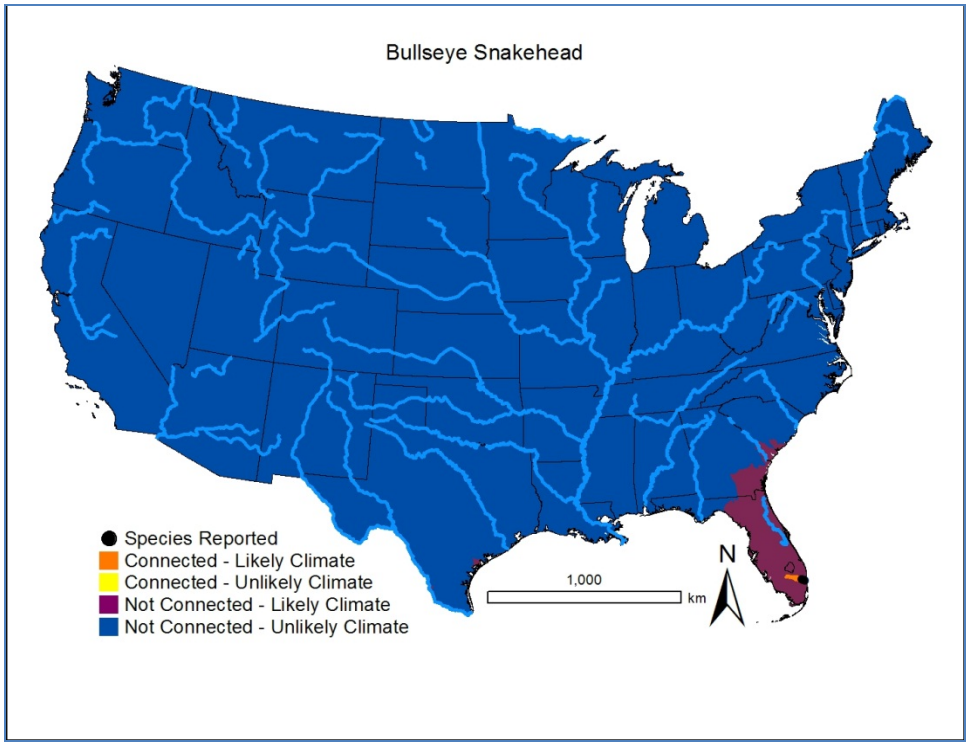


Figure 200. Nationally Prioritized Clima-Con Maps for Bullseye Snakehead. Connected shows areas where snakehead is present and could invade via connected waterways. Not connected shows connected waterways where snakehead is currently not present.

Potential Dispersal of Recently Established Populations in the Mississippi River

Past observations of snakehead invasions indicate that these species are capable of rapid population growth and high dispersal rates following initial introduction. For example, since the discovery of northern snakehead in Arkansas in 2008, the species has continued to spread into novel environments with the assistance of consistent flood events. Presumption of where initial specimens originated, a mile and a half from an aquaculture facility, and watershed sampling revealed more fish upstream than downstream suggesting that snakehead will migrate upstream more readily than downstream (Mark Oliver, AGFC, personal communication, 2014). This is consistent with dispersal behavior observed in the Potomac River (Lapointe et al. 2013). Snakeheads have only been documented occasionally downstream of the presumed point of origin; upstream migration is much more common. Although the reasons for this movement remain uncertain, these results signify that downstream migration may be a possible, but rare occurrence.

The greatest limiting factors for snakehead dispersal are river currents and availability of backwater areas, although movements of northern snakehead in the Potomac watershed have shown high gradients and swift currents are not migration barriers (Lapointe et al. 2013). With an abundance of backwater sloughs, ditches, and canals, snakehead are afforded an opportunity to disperse while avoiding strong currents as those found in the Arkansas and Mississippi Rivers. Numerous backwater areas in Arkansas has created

challenges for management, as these wetlands create multiple interconnected waterways during high water when fish can disperse to previously unconnected waters (L. Holt, AGFC, personal communication, 2012).

Based on observations in March and May of the population in Arkansas, northern snakehead prefer stagnant, vegetated back-water areas and do not readily reside in the main channel of streams. The preferred waters by northern snakehead in Arkansas are the interconnected irrigation ditches found throughout the farmlands in the east central part of the state (L. Holt, AGFC, personal communication, 2012). Similar habitats within the Mississippi River Basin may be at risk should a pathway to those waters become available (L. Holt, AGFC, personal communication, 2012).

Eradication and Control

Like many species, the potential for eradication is often dependent of the size of infestation and characteristics of the aquatic system in which they are found. The northern snakehead was successfully eradicated in two Maryland locations: from a 3 acre (1.6 hectare) storm water pond in Crofton with the use of rotenone and from 4 acre (2 hectare) Pine Lake in Wheaton by draining the lake with a pump. Eradication may not be economically viable or feasible in larger lakes or riverine systems where snakeheads have become widely established. Removal in smaller systems often depends upon the amount of vegetation, access to the water body, and effectiveness and availability of control methods.

If eradication cannot be achieved, population control measures can be used to maintain populations at lower levels; however such efforts require sustained resources. For such control measures to be effective, high removal numbers are often needed to observe a reduction in the population. The most effective control programs are integrated programs that use a variety of management options. Options for population control can include species removal, barriers, commercial and recreational fishery, and bounties or other incentive programs.

Removal control options include the use of general piscicides, such as rotenone, or physical removal methods such as electrofishing, nets, and/or traps. Removal methods are usually the most labor intensive and expensive. Population control methods for snakehead have been effective in small to medium, isolated water bodies or small order streams with limited riparian wetlands, but are often extremely demanding of resources (labor, equipment, etc.). Rotenone, for example, is a nonspecific piscicide that has been used to remove problematic fish in North America for over fifty years. Rotenone works by preventing fish from utilizing the dissolved oxygen in the water and also causes a neurological effect on certain species. Rotenone could be ineffective to air-breathing snakehead at low concentrations in open systems; however, it has killed northern snakehead in most applications. Electrofishing and netting can provide some level of control, but may not be efficient at capturing all size and age classes. These control methods also may not be effective within all habitat types (e.g., thick aquatic vegetation, extremely shallow water; J. Newhard pers. obs.). Electrofishing is inefficient in water with high salinity/conductivity due to current limitations of electrofishing technology. Moreover, its use is unlikely to result in eradication of a population, except perhaps during the earliest phases of establishment (USFWS, 2002). As technology advances, more options for controlling and ultimately, eradicating snakeheads may be available.

Commercial or recreational fisheries harvest may play a supplementary role within larger population control or eradication programs. Harvest from commercial and recreational fisheries has resulted in severe depression of biomass for many fish species in North America (Pauly et al. 1998; Secor 1999). However, there are some concerns related to promoting commercial or recreational fisheries harvest due to the possibility of

intentional release or propagation to support the fishery. If the demand and value for snakehead becomes high because of commercial or recreational fishing, then there is incentive to create breeding programs or intentionally release the species outside of currently established ranges (Pasko and Goldburg, 2014). Yet, if these concerns can be addressed, costs associated with commercial and recreational fisheries for snakehead would be less than the current removal methods.

In Maryland, the commercial sale of snakehead is in its infancy and will likely remain a small market (personal communication, S. Vilnit, Director of Seafood and Marketing, MDNR). The retail value of northern snakehead filets in 2014 in Maryland was about $44/kg with commercial anglers collecting about $11/kg whole fish dockside. The incentive to sell the species when caught reduces the high probability that commercial anglers would release the fish alive, which occurred when the species was first discovered in Potomac River. Moreover, a commercial reporting system was instituted by MDNR to track commercial harvest of snakeheads and MDNR works closely with fish wholesale distributors to ensure snakeheads are dead when sold. More importantly, MDNR continues to market northern snakehead as a mechanism to reduce biomass of an invasive species. While consideration must be given to prevent establishing financial incentive for individuals to relocate fish to create new, lucrative fisheries, there is no evidence that any snakeheads have been intentionally released for legal, commercial purposes in Maryland. None-the-less, commercialized harvest as a population control method for snakeheads should be carefully evaluated prior to development and implementation.

In addition, sport fishing for northern snakehead is becoming popular in the angling community. An annual Maryland recreational fishing tournament was held in June 2012, and in only 18 hours, over 200 snakeheads were caught, weighing over 1400 pounds (Fears, 2012). This tournament has been conducted each year since 2012 in partnership with MDNR and USFWS to teach anglers how to kill northern snakehead, when encountered, and the value of harvest in reducing biomass of the invasive species. Other sportfishing opportunities for northern snakehead have emerged, such as bowhunting and guiding. However, due to concerns that snakehead may be intentionally spread or propagated to sustain recreational snakehead fishing, NYDEC considered and rejected the idea of promoting the Meadow/Willow Lake snakehead population as a recreational angling opportunity (L. Surprenant, NYDEC, personal communication, 2013).

Bounties are another tool that may be useful in some cases. However, bounties on snakeheads have not been fully evaluated and a study of whether fishing pressure can be high enough for effective control may be useful. When northern snakehead was first discovered in Potomac River, Bass Pro Shops provided money in exchange for snakeheads that were harvested; that program stopped shortly thereafter. In the past states with bounties have never gotten heavy enough harvest pressure to eradicate the population. In addition to bounty programs, other incentives for anglers have been used to raise awareness, educate, and promote a desirable behavior from anglers. Since 2010, MDNR developed several incentive programs for anglers to learn to identify northern snakehead, to learn to how catch northern snakehead, and to ultimately harvest northern

snakehead as a mechanism of population control. As part of one of Maryland's earliest incentive programs, snakehead anglers uploaded a photo of a caught and killed northern snakehead to the Maryland DNR Angler's Log website to enter a random drawing. Three entries were selected to receive either a $200 Bass Pro Shops gift card, a Maryland State Sportsman Passport, or a Potomac River Fisheries Commission fishing license. The data were provided to USFWS and particularly in areas where it is first discovered, the program helped encourage the desired response of the angler, which was the harvest of the animal. Starting in 2013, northern snakehead was added to the list of species in the MDNR Volunteer Angler Survey which uses anglers' catch data to help fisheries managers assess fish populations. In addition to these incentive programs, MDNR currently offers an invasive species state record and fishing challenge awards for invasive species. While these awards are similar to the other state records and challenge awards offered by MDNR, the invasive species awards selectively reward anglers who harvest invasive species rather than releasing the animals alive.

In the absence of population control, snakeheads are likely to spread; although the extent of the spread is often dependent on the hydrology of the system. Within the Potomac River drainage, northern snakeheads spread rapidly throughout most of the drainage within seven years. This is roughly the same timeframe that Arkansas Game and Fish Commission estimate that snakeheads colonized approximately 434 miles (700 km) of streams and ditches within the Big Piney Creek watershed. Population control should be considered for established populations, even if negative impacts are not yet determined because there are often lag times between establishment of the invasive species and any observed impacts from that invader (Crooks, 2005). Given there is a high amount of suitable habitat for some snakehead species throughout the U.S. (Herborg et al., 2007), there is a high risk for snakehead to negatively impact native species (including threatened and endangered) and alter ecosystem processes. For a more detailed examination of the risks of snakehead establishment and impact, see the risk assessment by Courtenay and Williams (2004).

The costs associated with snakehead control need to be weighed against the potential monetary loss caused by the invading species. Costs for removing invasive species are almost always high (Allendorf and Lundquist, 2003; Pimentel et al., 2005). The benefits of control may be difficult to assign a monetary value, but may include reducing the spread to nearby watersheds and causing a national or regional problem. In recent years an average of $50 million has been spent annually on Asian carp control which includes monitoring, scientific research, operation of the electric barriers, eradication measures, and other population control, prevention, research, and outreach efforts. In the absence of Asian carp control, a more widespread problem could occur across a shorter time frame. In Arkansas, the costs associated with snakehead eradication attempts reached nearly $750,000. Control methods used included the application of powdered rotenone applied manually from ATVs, trucks, boats, and MarshMasters and liquid rotenone applied by helicopter. While snakeheads still reside in the Big Piney Creek drainage, the overall goal of protecting resources in the nearby White River National Wildlife Refuge and adjacent waters was achieved by delaying the spread of snakehead. Each instance

where snakeheads are managed will be unique as to whether the costs of control are greater than the possible harm of snakehead to the environment.

Incomplete information on snakehead life history and behavioral patterns creates challenges for removal efforts. As more is learned about snakehead behavior in U.S. waters, it will be easier for resource managers to strategically target control actions when capture efficiency is high, possibly also reducing costs. For example, demographic models have shown that removal of northern snakehead should occur during pre-spawn periods or prior to juvenile dispersal in order to be the most efficient in limiting population growth (Jiao et al., 2009). This is also the time period when northern snakeheads are more easily captured by electrofishing due to limited movement of adults (Lapointe et al., 2010). Furthermore, snakeheads appear to be most active during peak daylight times, suggesting targeted removal should occur during early morning or late evening hours when fish are less active. Based on data collected by USFWS, it is least costly for agencies to target northern snakehead when catch per unit effort (CPUE) is highest in the spring and fall when snakehead movements are limited. Snakehead control efforts should consider individual state laws which may also allow or restrict certain activities that can be conducted; for example some states do not allow the possession or sale of snakehead, dead or alive.

With any control effort, public information campaigns should be initiated. These should address any concerns the public may have regarding the control methods impact on the environment, whether it is natural, social or economic impacts. This can include any potential issues the public, may have through direct or indirect interactions with snakehead, or specific control methods such as electrofishing efforts, or rotenone application. The snakehead population control efforts conducted in Maryland in 2002 and Arkansas in 2009 required an address of public health and safety concerns with the use of rotenone. Such outreach is costly to agencies and requires time, training, and productive communication. The AGFC requested USFWS assistance with the control program and they participated due to the snakehead threat to the White River National Wildlife Refuge. Because of the USFWS federal involvement, an Environmental Assessment (EA) evaluating the effects of snakehead control was completed by the USFWS. The results of the EA provided a Finding of No Significant Impact (FONSI) for the Big Piney Creek drainage. Once the FONSI was accepted, AGFC was able to obtain full assistance from the USFWS in the control effort. The EA's and permits are often necessary in instances where snakeheads need to be eradicated or controlled, especially in instances when natural or cultural interests, public health or safety or violation of federal, state, local or tribal regulation may be encountered (43 CFR 46.215).

Early Detection and Rapid Response (EDRR)

Early detection and rapid response (ERDD) of snakehead invasions is key to preventing their establishment in new areas. Effective ERDD depends on several steps that are explained in this section. The steps to detect and respond to snakehead invasions require coordination with multiple agencies and organizations. These steps are a guide and any lessons learned can be applied to improve the process.

Site selection

Using the framework for assessing site vulnerability developed by Vander Zanden and Olden (2008), we recommend site selection for snakehead surveillance focus primarily on the potential for introduction and habitat suitability and less on the likelihood of adverse impacts since there is a scarcity of ecological data. The importation of snakehead is prohibited by the Lacey Act, significantly lowering the probability of new introductions into the U.S. However, this threat may be dependent on the effectiveness of inspectors to detect illegal imports of snakehead through import surveillance programs and the success of enforcement and prevention programs. In the interim, forecasting the probability of new introductions should focus on the potential for secondary spread from established populations. This will require a spatial assessment of both human-mediated pathways of spread and the likelihood for natural dispersal and intersection with suitable habitats. Priority should then be given to high probability sites with suitable habitat where adverse impacts are likely. An impact assessment needs to consider both the presence of vulnerable high-value species (e.g. threatened species or commercial fisheries), ecosystem services, and whether the site could facilitate or accelerate secondary spread (Worrall, 2002).

Sampling periodicity

Detecting an incipient invasion is often challenging when the target species is rare or elusive; however, this action is best achieved by either increasing sampling effort or adopting highly sensitive surveillance methods (McDonald, 2004). Determining the frequency in which a site should be sampled will require an understanding of the propagule pressure and the lag time between introduction and establishment. Data from the Potomac River population show that northern snakehead exhibit high fecundity, an early age of maturation, and multiple spawning events per year. These characteristics suggest that snakeheads are capable of high population growth and rapid range expansion. Accordingly, sites with a high vulnerability to invasion (sensu Vander Zanden and Olden, 2008) will require regular monitoring efforts in order to maximize the probability of detecting new snakehead incursions while they can still be contained and eradicated.

Sampling methods

Surveillance monitoring may incorporate a range of capture methods including electrofishing, traditional sampling gear, contract fishermen, and eDNA analysis. The methods used are often dependent on the characteristics of the habitat under consideration and resources available. Multiple methods are often beneficial to sample a full range of

habitats and maximize the probability of detection. Sampling results and data collected will contribute to the understanding of snakehead and help guide response actions.

Current detection methods for snakehead often rely on standard fisheries methods (traps, nets, electrofishing, etc.). These methods are most effective in shallow <3.3 ft. (< 1m), clear, and slow flowing water; however limited detection sensitivity may be present in deep, turbid waters or if snakehead are in low densities (L. Holt, AGFC, personal communication, 2012). Chemical treatment may also be used in place of, or in addition to these standard methods. The AGFC has found that spot treatment of sites suspected to contain snakehead with rotenone has been an effective method to survey short river reaches or ponds. However, widespread application of rotenone is often hindered by potential impacts to non-target species and difficulties in obtaining use permits. Indirect genomic detection tools (e.g. eDNA; Ficetola et al., 2008; Jerde et al., 2011) offer potential as an effective early detection surveillance method.

Various initiatives are underway to design and test genetic markers for snakehead species and quantify relative sensitivity and efficacy of eDNA analysis compared with standard fisheries methods. Methods utilizing eDNA have been used extensively throughout the Upper Mississippi River Basin and parts of the Great Lakes Basin to monitor for the possible presence of Asian carp. This technique could prove useful for early detection of snakehead as it has the potential to detect the presence of eDNA in the water when fish populations are at low levels (Jerde et al., 2011). The methodology and data interpretation of eDNA analysis are evolving rapidly (Lodge et al., 2012; Thompson et al., 2012), yet genetic laboratory capacity remains limited. For example, sample processing and analysis time can be variable and results may not be available for days to weeks. Currently, the positive detection of eDNA indicates presence only of the target species DNA (Thomsen et al., 2012). Although, a positive detection may be open to interpretation (see Darling and Mahon, 2011), the presence of a target species DNA may be a useful tool in determining areas where additional monitoring may be necessary, possibly using traditional sampling methods to confirm the presence of the target species. (Jerde et al. 2011, 2013). To maintain a responsive program, efforts for surveillance should focus on the tools currently available while continuing to develop additional methods to increase effective monitoring and early detection.

Rapid Response

Rapid response is a systematic effort to eradicate or contain invasive species while infestations are still localized (NISC, 2008). Clearly defined agency responsibility and action paths are critical to a timely response to any snakehead introduction. It is advisable that an organizational structure be established to ensure the exchange of information between appropriate agencies and stakeholders as well as to identify and establish the appropriate roles and leadership needed to initiate an effective response. This structure may be obtained using the Incident Command System (ICS), a standardized yet flexible, on-scene, and all-hazards incident management approach. ICS has earned a reputation as an “all risk, all hazard” response tool. Originally developed by the U.S. Forest Service, and now recommended by the Aquatic Nuisance Species Task Force, agencies such as the Animal and Plant Health Inspection Service (APHIS),

Environmental Protection Agency (EPA), the Department of Homeland Security (DHS), National Oceanic and Atmospheric Administration (NOAA), and the U.S. Coast Guard (USGC), use ICS to improve response to incidents from natural disasters and animal health emergencies to oil spills. The ICS is a subcomponent of the National Incident Management System (NIMS), as released by the U.S. Department of Homeland Security in 2004. NIMS training is available on line from the Emergency Management Institute (http://training.fema.gov/IS/NIMS.aspx).

The goal of the rapid response is to mitigate the potential adverse effects of an invading invasive species through containment, control, or eradication of the target population. Advanced planning and preparations are crucial to the success of a rapid response for agency collaboration, stakeholder and public buy-in of the potential actions, effective resource management, and to fulfill regulatory requirements.
Rapid response involves three key elements; a Response Trigger, Rapid Response Operations, and a Reverse Trigger. Each of these key elements is outlined below:

Response Triggers
The threshold or incident that triggers a response should be determined by the lead jurisdictional authority, with careful consideration given to the potential risk posed. The following thresholds or a combination of two or more threshold limits may be considered as triggers to invoke rapid response actions in a given area.

1. Agency observation or capture of one or more live snakehead specimen in a section of waterway and/or;
2. Multiple public reports or sightings of snakehead from a single location and/or;
3. Consecutive positive eDNA results for snakehead from a single location.

The final decision to initiate a rapid response action and the type and extent of the action ultimately will be based on the best professional judgment of representatives from involved agencies with jurisdictional authority. If a very small population is detected, containment and capture by local authorities may be sufficient. However, larger, self-sustaining or spreading populations may warrant a broader response, possibly involving multiple agencies at the regional and local scale. The decision to implement a rapid response action should account for the efficacy and capabilities of each trigger threshold met.

These responses are dependent on a variety of factors including the connectivity of the affected waterway, potentially affected species, and level of threshold met. The level of response is to be determined by the involved agencies in the impacted area with jurisdiction authority. A trigger/tiered response matrix should be developed to assist stakeholder agencies in the decision making process. This written record can be used to communicate and describe risks, events, or criteria that should be met to trigger a response action to all involved stakeholders. Additionally, this can be used to predetermine what type of response action will be taken in the event that certain thresholds of introduction are discovered (i.e. the discovery of one live specimen vs. an established breeding population in a given area).

Rapid Response Operations

Implementation of a rapid response operation consists of four phases: preparedness, response, recovery, and mitigation. Specific operational procedures will be dependent upon the treatment selected at the time of plan initiation.

Preparedness Phase. This phase begins well in advance of implementing operations in response to the threat of snakehead introductions or expansion into new waterway systems. It signals the threat is imminent and shall be executed by a response trigger. Since snakehead discoveries are unpredictable, states should have plans in place prior to the "response phase". This phase includes the following planning functions necessary to carry out a rapid response:

1. Selection of a rapid response planning team from stakeholder and partner agencies or organizations
2. Review of current legislation regarding AIS authorities and proposed treatment options
3. Request of information, support, and resources from stakeholder representatives to implement a rapid response
4. Assurance that Memoranda of Understanding (MOU) or other agreements are in place for efficient operations
5. Access to appropriate training for response (e.g., rotenone training, electrofishing training, etc.)
6. Site selection for treatment and staging (This can only be pre-determined if the invasive location is known in advance.)
7. Selection of potential treatments or response actions, ranging from increased monitoring to piscicidal treatments, best suited for various locations

Response Phase. This phase of the rapid response operation is initiated by the pre-established triggers and includes the response action as well as follow-up monitoring. The following functions occur within this phase:

1. Stakeholder notification – Stakeholder agencies should be notified of potential response actions and involved in the planning and response, if applicable.
2. Mobilization – Implement a National Incident Management System, Incident Command System (ICS).
3. Treatment selection and application – A tiered, integrated treatment response based on the severity of the threat, potential for spread of snakehead into new areas, and environmental or social concerns should be implemented. Response actions may include one or more of the following actions:
    a. Increase and sustained monitoring for a specified amount of time
    b. Use of piscicidal agent to further mitigate spread of snakehead fish present
    c. Initiate supplementary actions including, but not limited to, the following:
        i. Assess potential impacts to threatened and endangered species and live capture of sport fish and other critical species

        ii. Seine/block off the treatment area during operations to further isolate treatment area
4. Closing of structures such as sluice gates, dams, or navigable waterways where possible to prevent escape of fish during treatment
5. Detoxification, if necessary – (If a piscicide is employed, a detoxicant should be used to neutralize the agent so that it does not persist in the water and cause harm to additional native species in the area.)
6. Restoration of disturbed areas to minimize the risk of other non-native species invasion
7. Follow-up monitoring utilizing electrofishing, netting, eDNA analysis, or sentinel fish for snakehead presence

Reverse Trigger. The reverse trigger is the point at which the lead jurisdictional agency and/or its' response partners agree that incident requiring response has been addressed. One or all of the following may signal conclusion of response activities, depending on response actions implemented:

- Completed detoxification of treatment area
- Conclusion of cleanup actions
- Maximum piscicide dose achieved
- Dose timeline complete
- Negative monitoring result of snakehead sentinel fish
- Conclusion that control or eradication is not possible

The reverse trigger is composed of the recovery and mitigation phases, described below:

Recovery Phase. The recovery phase follows the water treatment and/or termination of the threat of snakehead species within the treatment area. This phase may begin during follow-up monitoring activities, and consists of recovery efforts. This phase concludes with the After-Action Report (AAR) and dissemination of lessons learned. The AAR is intended to assist agencies by analyzing results and identifying strengths to be maintained and built upon, identifying potential areas for further improvement, and recommending follow-up actions. The components of the Recovery Phase to be considered are as follows:

1. Continue follow-up monitoring efforts
    a. Determine capture from response operations and monitoring activities
2. Cleanup and dispose recovered fish and bio-mass from the treatment area
3. Demobilization
    a. When the reverse trigger has been met, demobilize personnel and resources until recovery is complete.
    b. Demobilize personnel and equipment according to the predetermined demobilization plan. Ideally, a demobilization plan should be prepared in advance of mobilization and communicated to all personnel to ensure proper documentation is achieved and procedures are followed. Plans generally include information to be collected for all personnel and

equipment, location of destination, signature of release, and procedures for travel and decontamination as needed.

4. Document costs associated with operations
    a. Compile costs expended by each agency including man-hours, equipment usage costs, consumables, and all other associated costs.
5. Preparation of an AAR
    a. Compile responder debriefs, lessons learned, and recommendations for future planning and response work.
6. Preparation for future response
    a. Base future responses on AARs, and lessons learned.
    b. Continue to train and exercise potential responding staff.

Mitigation Phase. The mitigation phase should begin following the recovery phase. During this phase improvement plans should be developed and implemented using the areas for improvement identified by the AAR. The mitigation phase may include of the following:

1. Development and implementation of a program Improvement Plan (IP)
2. Personnel training and rapid response exercises
3. Increase response capacity and capabilities

Current Research

The most effective strategy for preventing the introduction and spread of invasive species is through prevention programs. This involves identifying pathways to introduction and spread and engaging jurisdictions to consistently enforce laws. Once an invasion is discovered, agencies need to use all available resources and tools to eradicate or manage the invasion. The earlier the invasion is stopped, the more cost effective the eradication. It is important that agencies and stakeholders develop an invasion prevention and control strategy that includes prioritizing research needs that will address prevention priorities. The following is a discussion of components of a research strategy that are needed for an effective snakehead control and management program. Based on this and other data, managers should coordinate priority snakehead research.

The scale of both legal and illegal movement and sale of snakehead needs to be assessed, and reasons for these behaviors understood before effective prevention measures can be developed. Additional research is required to develop a better understanding of the life history characteristics of snakehead and more effective control methods. In addition, current methods of controlling snakehead populations may not offer complete control or eradication and can be extremely costly.

Current research activities for snakehead include creel surveys that provide data regarding how often recreational anglers catch snakehead and examine catch rates of species that may be negatively impacted by the presence of snakehead. This information is beneficial to determine if populations are expanding in range and/or growing in numbers and should continue every 2-3 years to monitor recreational catch rates of northern snakehead and other species.

In spring 2009, a cooperative tagging program for northern snakehead began on the Potomac River, conducted by state and federal agencies, including the District of Columbia Department of the Environment's Fisheries and Wildlife Division, MDNR, VDGIF, and USFWS. In this program, northern snakehead were tagged externally and released. Once captured and killed by recreational anglers, the tagged fish are reported to USFWS. These tag returns provide essential information on northern snakehead distribution and movement within the Potomac River. By April 2011, over 1133 northern snakehead were tagged in the Potomac River. Of these tagged fish, ninety-six were recaptured by both state or federal agencies and recreational anglers. The majority of recaptured northern snakehead (approximately 90 percent) remained in the creeks where they were initially tagged. This suggests that many individuals in the population do not move great distances. However, those individuals that did move outside the creek where they were initially tagged were capable of moving relatively large distances. One tagged fish was captured approximately a year after it was tagged, and had moved 29 river miles (47 km) upstream. Most northern snakehead movement appears to be during the pre-spawning months of April and May and during high flow events thus containment in large, open systems may be difficult (USFWS, unpublished data, 2012). Specific research methods and needs are identified in Objective 4 of this Plan

Education and Outreach

The effectiveness of the actions summarized in this Plan can be significantly enhanced through effective communication and increased public participation. Communication between agencies and outreach to the general public, commercial and recreational users, media, legislators, and local officials is critical to the success of snakehead control and management. An informed public is an essential component for improving the chances of preventing or minimizing impacts from snakehead.

Education and outreach information for the public and stakeholders is available in several places online including USDA's National Invasive Species Information Center snakehead page at http://www.invasivespeciesinfo.gov/aquatics/snakehead.shtml. This website offers information regarding all aspects of the snakehead management actions and includes links to important federal, state, and other relevant actions and information. Enhanced access to scientific literature on pathways, non-native fish species, and scientific research will improve the development of outreach materials and prevent future introductions of snakehead or other invasive species, improve our understanding of snakehead populations, and control methods, and improve our ability to implement the actions in this and future invasive species management plans. A central location for information on scientific literature on pathways and non-native fish species is important for coordinated management of snakehead. The National Invasive Species Information Center's snakehead page, U.S. Geological Survey, Non-indigenous Aquatic Species (USGS NAS) database (http://nas.er.usgs.gov/), or another website should be designated as the central information source and reliably funded and maintained to support snakehead control and management.

Preventing invasion and detecting snakehead starts with public education, specifically the live food markets, aquarium trade, and fishermen. Anglers, aquarists, fish markets, and the general public education could include providing a short, concise and easily understood poster, brochure, or information card. For example, these cards and brochures could be distributed through a multi partner campaign to the public and fishermen each time a fishing license is sold, a boat is registered, or aquarium fish are sold.

Educational material should notify anglers, aquarists, fish markets, and the public of the potential for snakehead to invade local waters and provide the capability to identify a snakehead. Materials should include phone numbers and contact information for the agencies involved with invasive species management. An explanation of natural resources stewardship, environmental and human health issues related to the introduction of snakehead, and regulations and penalties associated with live possession of snakehead could be included on outreach materials. It is critical to inform the public and all appropriate stakeholders of appropriate actions to be taken if a live snakehead is encountered. Educational programs and materials should be updated if regulatory status changes or new pathways are identified. The public may report invasive species

sightings, including snakehead at 1-877-STOP-ANS and http://nas.er.usgs.gov/sightingreport.aspx.

Such outreach materials should be in location specific languages and be distributed to fishing license holders and posted at boat ramps, bait and tackle shops, pet shops, fish markets, and cultural festivals. Public education is important since people may transport fish not realizing the environmental risks and legal penalties.

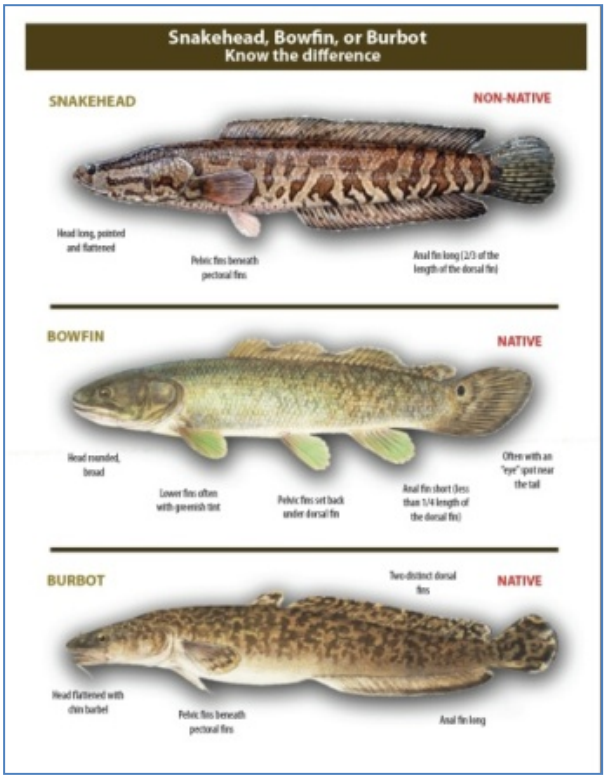


Figure 21. Poster on snakehead identification, including contact information, New York Department of Environmental Conservation (NYDEC)

Education programs and materials should be further tailored to inform inspection agents and state and federal wildlife officers about identification of live juvenile and adult snakehead, applicable laws, and high risk pathways.

Proactively working with the press can effectively spread a message to a wide population. Regular news releases and media events about the snakehead and other regional invasive species will bring attention to invasive species issues and highlight the activities of the Aquatic Nuisance Species Task Force. Each jurisdiction should have one point of contact for the press to ensure an accurate and consistent message. One central location, such as a website, could be established for the public and the press to obtain accurate and up to date information on snakehead biology, distribution, reporting, and management. Points of contact and other general information about snakehead could be posted on a snakehead website as part of a press kit for developing news releases and hosting media events.

Outreach efforts start with engaging key outlets and audiences. Utilizing media (newspapers, radio stations, and websites) can effectively communicate the threats to the ecosystem and economy; what can be done to prevent snakehead movement; and what penalties are associated with introduction, transport, and live possession of snakehead. Although there are many potential audiences, this plan encourages primary outreach efforts targeting angler and enforcement officer audiences. Table 5 identifies additional key outlets and audiences for outreach activities. These outlets are not listed in any priority.

Table 5. Key outlets and audiences for outreach activities involving snakehead

Key Outlets and Audiences for Outreach Activities	
Outlet	**Audience**
Academia and Research Community	Schools/Students Universities
Community Groups	Angler groups Community organizations groups
Consumers	Food consumers Recreational and farm pond owners
Elected Officials	Federal State Local
Enforcement	Homeland Security Local Municipality Enforcement Divisions and Peace Officers State Environmental Conservation Officers and Game Wardens US Border Patrol US Coast Guard US Fish and Wildlife Service
Marketers	Fish farms Live haulers Retail sales (grocers and pond stockings) Wholesalers
Media	Applications Blogs Magazines Newspapers Radio Television Widgets
Natural Resources Management Agencies/Organizations	Bureau of Land Management Land Grant institutions Local municipalities National Park Service NOAA Sea Grant institutions Non-governmental organizations Regional Aquatic Nuisance Species Panels State commerce agencies State DNR/DEC/DEP/AGR agencies State/County DOT agencies Tribal natural resources management agencies U.S. Army Corps of Engineers U.S. Department of Agriculture U.S. Department of Transportation U.S. Environmental Protection Agency U.S. Fish and Wildlife Service U.S. Forest Service U.S. Geological Survey
Pet Trade Industry	Aquarium and water garden owners and hobbyists Internet trade Retail store owners Wholesalers

Producers and Growers	Grow-out facilities Hatcheries
Recreational Anglers and Boaters	BASS groups Boating and sailing clubs Division of Motor Vehicles Large- and small-scale bait/tackle shops Marinas Trout Unlimited
Trade Associations	Commercial Fishers Commercial and Recreational Baitfish Harvesters Marine Trade Associations
Transporters	Consumers Fish farms Live haulers Retail sales Wholesalers

Appendix A. Objectives and Action Items for Plan Implementation

Plan Goal: Use the best available science and management tools to prevent the future introduction of snakehead into new areas, contain and, where possible, eradicate newly established and localized populations, and minimize impacts in areas where they are established and eradication is not feasible. The following objectives set forth by the Plan Development Committee are necessary to achieve this goal.

Table 6. Plan objectives and action items summary
Additional action items detail is below.

Objective	Item
Objective 1. Prevent new introductions of snakehead within the U.S. by refining regulations and improving compliance and enforcement.	1.1) Work with federal agencies, states, the District of Columbia, and jurisdictions to promulgate regulations or statutes that would prohibit possession, transportation, sale, acquisition, and introduction of all snakehead species nationally. 1.2) Improve border surveillance methods. 1.3) Promote the enactment of consistent and enforceable regulations and statutes among bordering or shared jurisdictions that include substantial penalties for violating those statutes. 1.4) Continue effective law enforcement to stop supply routes, sources, and markets. 1.5) Identify and understand vectors of spread and assess their risk of contributing to range expansions. 1.6) Identify options available to reduce the risks associated with each identified pathway. 1.7) Through genetic analysis, determine source regions of established populations and establish and maintain a population genetics baseline that describes genetic variation in established populations of snakehead in the U.S. 1.8) Determine the status of all snakehead introductions in the U.S.
Objective 2.0. Contain the expansion of northern snakehead within the U.S. by establishing an effective snakehead surveillance program to detect new introductions at a stage where populations are able to be removed.	2.1) Ensure all established populations are fully contained, and, where possible, eradicated. 2.2) Develop an information system via the web or protocol to notify other jurisdictions of sightings of snakehead. 2.3) Incorporate monitoring for snakehead into other existing aquatic surveys. 2.4) Establish a network of surveillance monitoring stations at priority sites. 2.5) Identify the most effective snakehead surveillance methods and develop guidelines and best management practices. 2.6) Identify legal and administrative processes that would streamline rapid response efforts. 2.7) Enact legislation in jurisdictions to allow the appropriate agency access on public and private property and inter-jurisdictional waters to conduct management activities. 2.8) Recommend that jurisdictions develop a rapid response plan for snakehead. 2.9) Obligate funding or identify sources of funding for rapid response.

Objective 3. Mitigate impacts of snakehead in U.S. waters where eradication is not possible.	3.1) Ensure all sources of snakehead in the U.S. are contained and, where possible, eradicated. 3.2) Compile a list of existing control options and summary of regulatory use requirements and develop best practice guidelines. 3.3) Petition EPA to develop a special use permit for the new rotenone label to address snakehead control. 3.4) Evaluate ecological and economic impacts of eradication. 3.5) Determine ecological and economic impacts of control methods. 3.6) Determine effectiveness of control options for long-term management.
Objective 4. Conduct research to understand pathways and to develop more effective surveillance, control, and eradication methods.	4.1) Conduct research on potential snakehead economic impacts to inform long-term control options. 4.2) Obtain information to better predict where snakehead could successfully establish. 4.3) Conduct research to understand snakehead life history and ecological effects on native aquatic communities. 4.4) Complete a risk assessment for each snakehead species to determine potential establishment, impact, and pathways for introduction.. 4.5) Test the efficacy of eDNA detection methods. 4.6) Determine the effectiveness of containment methods that prevent spread from infested areas. 4.7) Conduct research to develop additional control methods. 4.8) Conduct comprehensive review and translation of non-English literature on snakehead where the species is either native or naturalized. 4.9) Conduct a symposium to compile and publish scientific information pertaining to snakehead.
Objective 5. Develop outreach tools to help prevent new introductions of snakehead within the U.S. and control the spread of established populations.	5.1) Develop outreach tools for target groups to reduce risks of snakehead introductions. 5.2) Develop a press kit for jurisdictions to use communicating during management activities. 5.3) Develop instructions for the public to report sightings. 5.4) Train state and federal wildlife officers, U.S. Customs and Border Protection Inspectors. 5.5) Coordinate outreach efforts with those for other non-native fish species**.**
Objective 6. Review and assess progress of the Plan.	6.1) Annually review progress in the Plan. 6.2) Coordinate reporting and communications among stakeholders associated with implementation of actions in the Plan into a national website or database clearinghouse.

Objective 1. Prevent new introductions of snakehead within the U.S.

1.1. Work with federal agencies, states, the District of Columbia, and jurisdictions to promulgate regulations or statutes that would prohibit possession, transportation, sale, acquisition, and introduction of all snakehead species nationally.

The following actions are recommended:

- Establish a snakehead working group to identify regulatory gaps between jurisdictions.

- Consider a statutory requirement for states to report injurious wildlife species to USFWS.
- Draft model AIS regulations template for use by states to develop standard state regulations.

1.2. Improve border surveillance methods.

To prevent importation from vector source the following actions are recommended:

- Assess levels of illegal importation.
- Identify all methods of importing live snakehead, such as purchase through websites or hobbyist groups and inform them of the risk and application laws regarding snakehead.
- Develop Standard Operating Procedures (SOPs) improved border inspection methods that determine whether snakehead are being imported as contaminants and/or hidden within larger live fish importation.
- Develop practices for collecting samples that meet legal standards for chain of custody, etc.
- Evaluate efficacy of genomic screening compared to current surveillance methods, including considerations of sample collection and required process times.
- Develop eDNA screening to validate accuracy of visual inspections screening.
- Provide snakehead species identification, and high-risk source identification and law awareness training to state and federal wildlife officers, and U.S. Customs and Border Protection Inspectors.

1.3 Promote the enactment of consistent and enforceable regulations and statutes that include substantial penalties for violating those statutes.

Establish a working group to help each state jurisdiction to:

- Develop the same regulations to prevent further spread or introduction of snakehead into new areas.
- Prohibit the possession transportation, sale, acquisition, and introduction of live snakehead and establish state border surveillance programs.

1.4 Continue effective law enforcement activities to stop supply routes, sources, and markets.

The following actions are recommended:

- Strengthen coordination between natural resource managers and law enforcement to implement the most effective tools to prevent new introductions the spread of established populations into new areas.

1.5 Identify and understand vectors of spread and assess their risk of contributing to range expansions.

Assessing the risk of introduction associated with each identified pathway will assist states and jurisdictions in prioritizing enforcement and outreach efforts to prevent additional introductions of snakehead. The following actions are recommended:

- Monitor the live food fish market as the main vector for introduction of snakehead.
- Assess whether animal release via religious ceremonies is a real vector for introduction of snakehead species.
- Assess the probability of anglers unintentionally introducing snakehead through catch and release or the release of live bait. Efforts could include site visits to local bait shops and distributers for, visual inspections, eDNA sampling, and questionnaires.
- Initiate undercover visits to fish markets and pet shops to detect possible violating and state and federal laws regarding snakehead.

1.6 Identify options available to reduce the risks associated with each identified pathway.

The following action is recommended:

- Agencies and organizations should conduct regular reviews of their invasive species programs to identify improvements needed to surveillance, management as well as outreach and enforcement activities.

1.7 Through genetic analysis determine source regions of established populations and establish and maintain a population genetics baseline that describes genetic variation in established populations of snakehead in the U.S.

Agencies involved in inspections and enforcement at ports of entry need information to determine which countries are importing snakehead illegally to help determine whether new introductions represent illegal importation from outside U.S. or spread within the U.S. from known populations. The following actions are recommended:

- Identify the genetic makeup of all populations of snakehead worldwide.
- Identify and fully characterize the genetic origin of all snakehead populations and single records presently within the U.S., as well as Canada and Mexico, to provide a population genetics baseline that will enable the source of future introductions to be assessed.

1.8. Determine the status of all snakehead introductions in the U.S.

Uncertainty is still present in sites where single or small numbers of individual fish have been collected, namely Florida, California, North Carolina, Illinois, and Massachusetts. Snakehead range is unknown in many of these areas for many reasons, including limited resources and surveillance methods. The following actions are recommended:

- Determine the current population status of all snakehead occurrences.
- Develop and employ additional tools to help determine the status of snakehead outside their established range.

Objective 2.0. Establish an effective snakehead surveillance program to detect and respond to new introductions

2.1. Ensure all populations are fully contained, and, where possible, eradicated.

All established populations have the potential to act as sources of propagules for spread new populations should be contained to prevent natural and anthropogenical spread, and efforts should be made to eradicate. The following actions are recommended:

- In areas where snakehead have been introduced to establish a local wild food source, community action should be initiated to increase public awareness, surveillance, and enforcement.

2.2. Develop an information system via the web or protocol to notify other jurisdictions of sightings of snakehead.

To insure improved international and state border protection from AIS pathways by import and individuals, it is critical to notify bordering or shared jurisdictions when a snakehead is found. The following actions are recommended:

- Develop a national reporting and notification system via the web for prompt notification of new introductions and communication to adjacent states. NAS alerts from USGS are an example of an effective communication tool that may be used for snakehead.
- Encourage the public and agencies to report snakehead sightings and catches to populate the system.

2.3. Incorporate monitoring for snakehead into other existing aquatic surveys.

Monitoring programs for snakehead should be conducted in states where the fish has been introduced or a present a high risk of being introduced. The following actions are recommended:

- Identify routine monitoring of water bodies conducted by agencies and other organization that could be expanded to, incorporate snakehead surveillance into the efforts.

2.4. Establish a network of surveillance monitoring stations at priority sites.

The following actions are recommended:

- Identify priority sites for snakehead surveillance on the basis of the risk of invasion, habitat suitability and, presence of vulnerable taxa or ecosystems. Priorities for monitoring can be identified on the basis of an analysis of proximity to established populations and presence of vectors or pathways of spread.
- When possible, incorporate eDNA detection tools into surveillance and monitoring of high-risk pathways for snakehead introductions and inland waterways

- Conduct surveillance monitoring of pathways such as fish haulers (bait, fish stocks) or plants originating from areas with established snakehead populations within the U.S.

2.5. Identify the most effective snakehead surveillance methods and develop guidelines and best management practices.

The following actions are recommended:

- Identify the most effective and sensitive surveillance methods that maximize the likelihood that those new introductions will be detected early, while they are still localized and can be contained and ideally eradicated.
- Compose guidelines to provide a consistent, effective method for snakehead surveillance that includes descriptions of monitoring methods and best management practices.

2.6. Identify legal and administrative processes that would streamline rapid response efforts.

Potential legal barriers that may prevent rapid response occurring in a timely manner should be identified along with corresponding solutions. The following actions are recommended:

- Streamline the NEPA process for evaluating federal actions that may affect the environment. This includes any federal assistance to state, local agencies, or organizations.
- The Federal agencies should consider developing a categorical exclusion for future snakehead control programs in instances where snakehead need to be eradicated or controlled, especially in instances when natural or cultural interests; public health; or safety or violation of federal, state, local or tribal regulation may be encountered (43 CFR 46.215).
- Develop processes to streamline Endangered Species Act (ESA) evaluations in advance of rapid response operations.

2.7. Enact legislation to allow the appropriate agency access on public and private property and inter-jurisdictional waters to conduct management activities.

Virginia legislation authorizes the VDGIF to control any nuisance species populations and gives the Department authority to obtain a warrant to conduct such operations on private property. In Maryland, there is legislation that authorizes the MDNR to enter and inspect property to determine if a “state of nuisance” exists, and establishes provisions related to abatement. However many other states lack legal authorization for state or federal agencies to enter private or restricted areas to conduct control operations; to remedy this situation, the following actions are recommended:

- Establish a working group to help state jurisdictions draft early detection and rapid response legislation enabling state agencies to enter private lands and take action to manage invasions legislation.

2.8. Recommend that states develop a rapid response plan for snakehead.

The ANSTF requires every state management plan to include a rapid response plan; however many state plans lack this component as they were submitted prior to this requirement. Each state should be encouraged to develop, or update if needed, a rapid response plan. The Mid-Atlantic Panel on Aquatic Invasive Species has developed guidelines for responding to an aquatic invasive species incident quickly and effectively (http://www.midatlanticpanel.org/resources/documents/MarylandPlanFinal.pdf). The Mississippi River Basin Panel on Aquatic Nuisance Species has also developed a model rapid response plan, including specific response procedures for aquatic invasive fish (http://www.mrbp.org/images/stories/Documents/MRBP/RapidResponse/fish%20addendum.pdf). Such document may provide a valuable resource for development of additional rapid response plans. Any protocol developed should:

- Use a standardized protocol, such as ICS, that allows for a common response framework across federal, state, local, and tribal agencies and jurisdictions
- Identify regulatory requirements including acquisition of required permits for control methods.
- Establish safety protocol for the control methods.
- Describe containment, control and eradication best management practices and their relative effectiveness.
- Identify and develop a directory of rapid response experts, agency personnel, scientists, and certified pesticide and herbicide applicators, and incursion response experts who can identify fish in question and recommend and implement containment and control strategies.
- Identify peer reviewed rapid response plans and ISC protocols for immediate availability.
- List contacts and key experts.
- Develop containment guidelines based on the type of aquatic system in which the introduction has occurred and incorporate into rapid response plans.

2.9. Obligate and identify sources of funding for rapid response.

The following actions are recommended:

- States at high risk for introduction of snakehead should plan, identify, and obligate sources of funding for rapid response. Agencies should work together to develop a rapid response fund that could be used for emergencies.

Objective 3. Mitigate impacts of snakehead in U.S. waters where eradication is not possible.

3.1 Ensure all sources of snakehead in the U.S. are contained and, where possible, eradicated.

While downstream invasion may not be preventable, it may be possible to prevent access to tributaries that flow into the lower Mississippi by establishing barriers, similar to those

used to protect the Great Lakes Basin from Asian carp. The following actions are recommended:

- Assess the development of barriers and other methods to prevent upstream dispersal.
- Instigate control and containment measures as soon as snakehead are detected to slow establishment and minimize impacts.
- In areas where snakehead have been introduced to establish a local wild food source, community action should be initiated to increase public awareness, surveillance, and enforcement.
- Confirm the possibility that there may be an active underground or black market for snakehead.

3.2. Compile a list of existing control options and summary of regulatory use requirements and develop best practice guidelines.

A list of different control options should be developed that could be used in a variety of environments. The following actions are recommended:

- Review past control efforts, both successful and ineffective, for lessons learned and reasons for lack of success.
- Compile regulations and best management practices that apply to complement the list of control tools.
- Develop new guidelines where gaps are identified.
- Periodically update the eradication tool list, regulatory requirements, and best practice guidelines as information on eradication strategies develops.

3.3. Petition EPA to develop a special use permit for a new rotenone label to address snakehead control.

Currently the rotenone label does not describe treatment of water bodies for snakehead. If biologists determine rotenone is the most effective control method for a project, they must apply for a special use permit from the EPA and state pesticide bureaus. This can be expensive, time consuming, and risks further establishment of snakehead. The following actions are recommended:

- The National Snakehead Management Plan committee should initiate the EPA process to amend the rotenone label to allow the treatment of water bodies for snakehead and allow more flexibility for concentration levels, application rates and notification.

3.4. Evaluate ecological and economic impacts of eradication.

Removal of snakehead may impact other species or habitats in negative or positive ways. In areas where snakehead is well established, its sudden removal may cause abrupt changes to trophic relationships and ecosystem processes. Ecological and economic impacts of eradication must be considered for different aquatic systems. The following actions are recommended:

- Evaluate the functional roles of snakehead within ecosystems and possible trophic interactions with native species, Use this information to determine any unexpected consequences for native species that may result for eradication
- Identify any non-target species that may be affected be the control measures used and evaluate the environmental and economic impacts of this unintended consequences for native species.
- Ensure that appropriate restoration and post-monitoring measures are taken following control re-establish pre-snakehead communities.

3.5. Determine ecological and economic impacts of control methods

The following actions are recommended:

- The effectiveness and feasibility of different control options in diverse systems should be evaluated. For example, piscicides would not be effective in a large, open aquatic system or able to be used in a reservoir that is a drinking water source. The following actions are recommended:
- Evaluate ecological risks and benefits to native flora and fauna and economic costs and benefits to determine which control strategies should be employed for long-term management. This is usually conducted as a part of the NEPA evaluation of a project.

3.6. Determine effectiveness of control options for long term management.

Current methods of controlling snakehead populations may not always offer complete control and can be extremely costly and require long-term commitment. The following actions are recommended:

- Conduct research to determine effectiveness of different control options for long-term management in different systems.
- Develop more efficient, integrated control strategies that use multiple methods to target vulnerable life stages or behaviors will improve the control program effectiveness. This adaptive management framework will provide flexibility if the characteristics of the invasion or control effectiveness changes.

Objective 4. Conduct research to understand pathways and to develop more effective surveillance, control, and eradication methods.

4.1. Conduct research on potential snakehead economic impacts to inform long-term control options.

There are still many questions regarding the potential economic impacts from snakehead. Research studies should include, but not be limited to, the following recommendations:

- Conduct studies to determine the economic impacts of snakehead.
- Conduct closed systems studies to determine potential food web shifts, reduction in sport fish abundance, and impacts to native species effects at the ecosystem and species level.

4.2. Obtain information to better predict where snakehead could successfully establish.

Research studies should include, but not be limited to, the following recommendations:

- Obtain spatial records across snakehead native range to inform development of niche models that represent the full U.S. distribution potential.
- Conduct biotelemetry and tagging studies of established populations to examine spatial and temporal distribution and understand the environmental drivers and limits of dispersal. Conduct studies to determine environmental and behavioral cues to movements to colonize new habitats.

4.3. Conduct research to understand snakehead life history and ecological effects on native aquatic communities.

Snakehead have not been methodically studied in their native habitat. Very little is known about the potential effects to native species and ecosystem services from of snakehead introductions in the U.S. There are still many questions regarding the life history of snakehead and the potential impacts from this species. Answering these questions is essential to better manage this species and protect natural resources. Research studies should include, but not be limited to, the following recommendations:

- Investigate the biology, behavior, movement, and stock dynamics of the snakehead.
- Determine baseline histology of snakehead to better understand the risk and mechanism of these species spreading parasites and diseases to native organisms.
- Support ongoing research and assist with initiating new research to develop clearer understanding of snakehead taxonomy as it relates to species identification (cryptic species, hybrids, and larvae) and life history.
- Determine methods for aging otoliths or scales and sexing snakehead to better understand population dynamics. This includes investigating possible sexual dimorphism, histology of testes in males, and examining non-gravid females.
- Conduct studies to investigate spawning, feeding, and guarding behavior to inform long-term control options.
- Conduct dispersal limits imposed by saltwater studies to understand the dispersal potential in the lower Mississippi delta and Gulf region.
- Identify and prioritize sites that contain rare or threatened taxa highly vulnerable to snakehead predation or competition.

4.4. Complete a risk assessment for each snakehead species to determine potential establishment, impact, and pathways for introduction.

The following actions are recommended:

- Update existing snakehead risk assessments (e.g. Courtenay and Williams, 2004)
- Conduct risk assessments for species and/or habitats not yet assessed.
- Promote use of risk assessments by resource managers to assist development of local snakehead surveillance and management plans. Two of these risk

assessment tools include The USFWS Risk Assessment and Mapping Program (RAMP) and the risk assessment conducted by Courtney.

4.5. Test the efficacy of eDNA detection methods.

The following actions are recommended:

- Evaluate the field efficacy of eDNA by developing and testing primers, standardized protocols, and SOPs for field sampling, laboratory analysis, and data validation.
- Ensure that analysis is rapid, accurate, reliable, and consistent with a nationally approved program. This is particularly important for data comparability.

4.6. Determine effectiveness of containment methods that prevent spread from infested areas.

The following actions are recommended:

- Evaluate options to develop new barriers that prevent upstream movement of snakehead.

4.7. Conduct research to develop additional control methods.

At this time, control options are extremely limited for snakehead, and successful control is often restricted to small to medium sized, shallow, and slow flowing water bodies. Successful management of snakehead requires that new integrated approaches using multiple methods of control options are developed and tested for effectiveness in different aquatic systems. Research studies should include, but not be limited to, the following recommendations:

- Evaluate the effectiveness of different field collection techniques for snakehead.
- Conduct studies to determine optimal exploitation or removal strategies designed to reduce snakehead abundance.
- Conduct analysis to determine if developing commercial fishery operations and markets for snakehead could reduce established populations.
- Improve electrofishing control measures by identifying the most effective electrical waveforms, current, and voltage required to capture, kill or damage all snakehead life stages. Develop snakehead specific capture methods and attractants.
- Develop baits or pheromone attractants to improve catch efficiency of nets and traps.
- Develop better understanding of the effectiveness of rotenone (liquid versus powder formulations) to improve success of eradication attempts.
- Develop species specific biocides or delivery mechanisms.
- Conduct research into snakehead parasites and disease vulnerability within their native and introduced range to inform potential biological control mechanisms.
- Investigate methods that interfere with adult nest guarding behavior and increase the vulnerability of larvae and eggs to native predators.

- Snakehead eggs and larvae both aggregate on the top of the water. Target eggs, larvae or other life stages when they are most vulnerable with rotenone treatments.
- Further develop and test genetic control tools including daughterless, sterile male approaches, or lethal genetic control tools.

4.8. Conduct comprehensive review and translation of non-English literature on snakehead where the species is either native or naturalized.

The following actions are recommended:

- Translate Japanese, Chinese, and Korean snakehead studies to English to provide information on life history and biology of snakehead in their native ranges and help predict potential ecological and economic impacts and inform long-term control and eradication options**.**

4.9. Conduct a symposium to compile and publish scientific information pertaining to snakehead.

The following actions are recommended:

- Conduct a symposium with published proceedings that focus on snakehead management to communicate and catalog research results in a timely manner to natural resource managers.

Objective 5. Develop outreach tools to help prevent new introductions of snakehead within the U.S. and control the spread of established populations.

5.1. Develop outreach tools for target groups to reduce risks of snakehead introductions.

The following actions are recommended:

- Create materials, such as posters or brochures in several different languages that focus on stewardship, health issues from consumption, and regulations or penalties associated with introduction, transport, and live possession of snakehead.
- Designate a liaison to communicate using various types of media (newspapers, radio stations, websites,) targeting boat ramps, fishing license holders, cultural festivals, and bait and tackle shops.
- Emphasize stewardship by citing examples where the introductions of other species have had high environmental or economic costs.

5.2. Develop a press kit for jurisdictions to use for communicating during management activities.

The following actions are recommended:

- Designate one point of contact for each jurisdiction that will communicate with the press and ensure a correct and consistent message.

- Develop outreach materials that include general information on the species and contact information to be posted on the national snakehead website (Action Item 6.2).

5.3. Develop instructions for the public to report sightings.

The following actions are recommended:

- Develop outreach materials and a template with snakehead identification, collection and reporting information that could be modified for local use. This will allow the public to easily identify snakehead from other similar looking species and ensure a consistent, accurate message. These materials could be posted on the national snakehead website (Action Item 6.2).

5.4 Train state and federal wildlife officers, U.S. Customs and Border Protection Inspectors.

The following actions are recommended:

- Response teams should be trained on the identification of species, use of eradication and management tools, public awareness
- Law enforcement agents should be trained on species identification of all live juvenile and adult snakehead, appropriate regulations for their jurisdiction.

5.5 Coordinate outreach efforts with those for other non-native fish species.

To provide greater effectiveness in preventing future introductions of new species the following actions are recommended:

- Coordinate with the ANSTF, NISC, and other groups in development and distribution of outreach materials that focus non-native fish species.

Objective 6. Review and assess progress of the Plan.

6.1. Annually review progress of actions in the Plan.

The following actions are recommended:

- The working group members should meet on an annual basis to review progress of implementation of management actions identified in the Plan, to prioritize actions, and to discuss potential funding sources.
- Develop performance measures to assess implementation progress. Measures should include key milestones of success and or failure. In addition, they should determine how success is defined (i.e. all populations are contained, range has contracted, key outlying populations are eradicated, or few new populations have been detected).

6.2. Coordinate reporting and communications among stakeholders associated with implementation of actions in the Plan into a national website or database clearinghouse.

Several data collection systems have been developed, but the information is not universally available, regularly updated, or consistent. A national level database for access by researchers, managers and even the public is needed. Several have been developed but need a lead manager and funding to make the information useable. The following actions are recommended:

- Collect and review information associated with implementation of management actions on a national website in a timely manner.
- Develop a snakehead URL that includes relevant research and cited literature and coordinates with states to collect data on a national scale.
- Promote and, if needed, develop new centralized national reporting systems (e.g., USGS – NAS Database). The National Invasive Species Information Center's snakehead page, U.S. Geological Survey, Non-indigenous Aquatic Species (USGS NAS) database, or another website could be designated as the central information source and reliably funded and maintained to support snakehead control and management.
- Develop a database for snakehead discovered at inspection points to detect importation trends.
- Consider coordinating existing databases and websites into one single centralized database that provides all the information needed to manage AIS.

Appendix B. Literature Cited

An asterisk (*) after the citation indicates that the reference is indirectly cited or is cited in other references.

Ahmad, M.U., F. Khumar, S. Anwar, and M.S. Siddiqui, 1990. Preliminary observations on the growth and food of the murrel *Channa* (=*Ophicephalus*) *marulius* (Bloch) of the River Kali in north India. Journal of Freshwater Biology 2: 47-50.

Allendorf, F.W. and L.L. Lundquist. 2003. Introduction: Population biology, evolution, and control of invasive species. Conservation Biology. 17: 24-30.

Anderson RP, Lew D, Peterson AT.2003. Evaluating predictive models of species' distributions: criteria for selecting optimal models. Ecological Modelling 162: 211–232

Atkinson, C.E. 1977. People's Republic of China, in Brown, E.E. ed., World Fish Farming, Cultivation and Economics, Westport, Connecticut, AVI Publishing Co., p. 321-344.

Baltz, D.M. 1991. Introduced fishes in marine systems and inland seas, Biological Conservation 56:151-177.*

Balzer, T., P. Balzer, and S. Pon, 2002. Traditional use and availability of aquatic biodiversity in rice-based ecosystems. I. Kampong Thom Province, Kingdom of Cambodia, Rome, Italy, FAO/Netherlands Partnership Programme "Awareness of Agriculture Biodiversity."

Bardach, J.E., J.H. Ryther, and W.O. McLarney, 1972. Aquaculture: The farming and husbandry of freshwater and marine organisms. Wiley Interscience: New York. Pp. 1-868.

Berg, L.S. 1965. Freshwater fishes of the USSR and adjacent countries, Vol III (4th ed., improved and augmented), [Translated from Russian; original 1949, Jerusalem, Israel]

Boesch, D. 2002. Snakehead Scientific Advisory Panel First Report to the Maryland Secretary of Natural Resources. Unpublished report to the Maryland Secretary of Natural Resources, Annapolis, MD, USA.

Bomford, M. 2008. Risk assessment models for establishment of exotic vertebrates in Australia and New Zealand, Invasive Animals CRC, Canberra.

Britz, R. Division of Fishes, National Museum of Natural History, Smithsonian Institution, Washington, D.C. personal communication, 2002.

Brown, J. H. 1989. Patterns, modes and extents of invasions by vertebrates. In: J. A Drake, H. A., Mooney, F. di Castri, R. H. Groves, F. J. Kruger, M. Rejmanek and M.W. Williamson (eds), e.g., Biological Invasions. A Global Perspective. John Wiley and Sons, Chichester. Pp 85–109.

Carpenter G, Gillison AN, Winter J.1993. DOMAIN: a flexible modelling procedure for mapping potential distributions of plants and animals. Biological Conservation 2: 667–680

Cohen, M.K., J.A. MacDonald, and A.M. Brinton. 2012. Northern snakehead in two New York City lakes over four years. American Fisheries Society, Fisheries Reports, http://www.dec.ny.gov/docs/fish_marine_pdf/meadwillrep.pdf.

Copp, G.H., L., Vilizzi, J. Mumford, G.V. Fenwick, M.J. Godard, and R.E. Gozlan. 2009. Calibration of FISK, an invasiveness screening tool for non-native freshwater fishes. Risk Analysis 29:457-467.

Courtenay, W.R., Jr., and J.D. Williams. 2004. Snakehead (Pisces: Channidae): A biological synopsis and risk assessment. U.S. Geological Survey Circular 1251, 143 p. http://pubs.er.usgs.gov/publication/cir1251

Crooks, J.A. 2005. Lag times and exotic species: The ecology and management of biological invasions in slow-motion. Ecoscience. 12: 316-329.

Darling J.A., Mahon A.R. 2011. From molecules to management: adopting DNA-based methods for monitoring biological invasions in aquatic environments. Environ. Res. 111: 978–988

Dasgupta, M. 2000. Adaptation of the alimentary tract to feeding habits in four species of fish of the genus Channa. Indian Journal of Fisheries 47: 265-269.

Dukravets, G.M. 1992. The Amur snakehead, *Channa argus warpachowskii*, in the Talas and Chu River drainages. Journal of Ichthyology 31(5):147-151.

Dukravets, G.M. and A.I. Machulin, 1978. The morphology and ecology of the Amur snakehead, *Ophiocephalus argus warpachowskii*, acclimatized in the Syr Dar'ya basin. Journal of Ichthyology 18(2):203-208.

Fears, D. 2012. Contest removes loads of snakeheads from Potomac. Washington Post. Available from: http://www.washingtonpost.com/national/health-science/contest-removes-loads-of-snakeheads-from-potomac/2012/06/03/gJQAe6nICV_story.html.

Ficetola, G.F., C. Miaud, F. Pompanon, and P. Taberlet. 2008. Species detection using environmental DNA from water samples. Biol. Lett. 4:423-425.

FAO (Food and Agriculture Organization of the U.S.). 1994. Aquaculture production 1986-1992 (4th ed.), Rome, Italy, FAO Fisheries Circular 815, 216 p.*

Frank, S. 1970. Acclimatization experiments with Amur snakehead, *Ophiocephalus argus warparchowskii* (Berg, 1909) in Czechoslavakia, Vstník eskoslovenské Spolenosti Zoologické, 34:277-283.

Freeze, M., Arkansas Game and Fish Commission, personal communication, 2004

Froese, R. and D. Pauly. Editors. 2011. FishBase. World Wide Web electronic publication. www.fishbase.org, version

Gabelhouse, D. Nebraska Game and Parks Commission., personal communication, 2012.

Galvez, J. USFWS (U.S. Fish and Wildlife Service)., personal communication, 2012.

Gestring, K., Florida Wildlife Commission, personal communication, 2001

Guseva, L.N., 1990. Food and feeding rations of the Amur snakehead, *Channa argus warpachowskii*, in water bodies in the lower reaches of the Amu Darya: Journal of Ichthyology 30:11-21.

Guseva, L.N. and I.M. Zholdasova, 1986. Morphoecological characteristics of the snakehead (*Ophiocephalus argus warpachowskii*) (Berg) as an introduced species in water bodies of the lower delta of the Amu Dar'ya, in Biological Resources of the Aral Region, FAN, Tashkent, p. 98-134.*

Herborg, L., N.E. Mandrak, B.C. Cudmore, and H.J. MacIsaac. 2007. Comparative distribution and invasion risk of snakehead (Channidae) and Asian carp (Cyprinidae) species in North America. Canadian Journal of Fisheries and Aquatic Sciences 64: 1723-1735.

Holt, L., Arkansas Game and Fish Commission, personal communication, 2012

Howells, R.G., Williams, J.D., and Courtenay, W.R., Jr., "Snakeheads Represent An Increasing Threat To U.S. Waters," ANS [Aquatic Nuisance Species] Digest Vol. 4, no. 4, Feb. 2002

Jang, M. H., G. J. Joo, and M. C. Lucas. 2006. Diet of introduced Largemouth Bass in Korean rivers and potential interactions with native fishes. Ecology of Freshwater Fish 15:315–320.

Jerde C.L., A.R. Mahon, W.L. Chadderton, D.M. Lodge. 2011. "Sight unseen" detection of environmental DNA for surveillance of aquatic organisms at low densities. *Conservation Letters* 4:150-157.

Jerde, C.L.**,** W.L. Chadderton, A.R. Mahon, M.A. Renshaw, J. Corush, M.L. Budny, S. Mysorekar, and D.M. Lodge. 2013. Environmental DNA detection of Asian carp as part of a Great Lakes basin-wide surveillance program. Canadian Journal of Fisheries and Aquatic Sciences. 70 (4): 522-526.

Jiao, Y., N.W.R. Lapointe, P.L. Angermeier, and B.R. Murphy. 2009. Hierarchical demographic approaches for assessing invasion dynamics of non-indigenous species: An example using northern snakehead (*Channa argus*). Ecological Modeling 220:1681-1689.

King, T.L. and R.L. Johnson. 2011. Novel tetra-nucleotide microsatellite DNA markers for assessing the evolutionary genetics and demographics of Northern Snakehead (Channa argus) invading North America. Conservation Genetic Resources 3:1-4.

Kottelat, M. 2001. Fishes of Laos. Colombo, Sri Lanka. WHT Publications. Pp. 1-198.*

Lapointe, N. W. R., Odenkirk, J. S., & Angermeier, P. L. 2013 Seasonal movement, dispersal, and home range of Northern Snakehead *Channa argus* (Actinopterygii, Perciformes) in the Potomac River catchment. Hydrobiologia: 1-15.

Lapointe, N.W.R., J.T. Thorson, and P.L. Angermeier. 2010. Seasonal meso- and microhabitat selection by the northern snakehead (*Channa argus*) in the Potomac river system. Ecology of Freshwater Fish 19:566-577.

Lee, P.G., and P.K.L. Ng, 1991. The snakehead fishes of the Indo-Malayan Region. Nature Malaysiana 16:113-129.

Liu, J., Y., Cui, and J. Liu, 1998. Food consumption and growth of two piscivorous fishes, the mandarin fish and the Chinese snakehead. Journal of Fish Biology 53:1071-1083.

Lodge, D.M., C.R. Turner, C.L. Jerde, M.A. Barnes, W.L. Chadderton, S.P. Egan, J.L. Feder, A.R. Mahon, and M.E. Pfrender. 2012. Conservation in a cup of water: estimating biodiversity and population abundance from environmental DNA. Molecular Ecology, 21(11) 2555-2558.

Love, J.W. and J.J. Newhard. 2012. Will the expansion of northern snakehead negatively affect the fishery for largemouth bass in the Potomac River (Chesapeake Bay, USA)? North American Journal of Fisheries Management. In press.

McDonald, L.L. 2004. Sampling rare populations. Pages 11–42 in W.L. Thompson, editors. *Sampling rare or elusive species*. Island Press, New York.

Minkkinen, S., USFWS (U.S. Fish and Wildlife Service), personal communication, 2012

Moyle, P. B. 1986. Fish introductions into North America: patterns and ecological impact. In: H. A. Mooney and J. A. Drake (eds), Ecology of Biological Invasions of North America and Hawaii. Springer, New York. Pp 27–43

NISC (National Invasive Species Council). 2008. 2008-2012 National Invasive Species Management Plan.

Nikol'skii, G.V. 1961. Special Ichthyology (2nd Edition). Published for the National Science Foundation, Washington, D. C. and the Smithsonian Institution, by the Isreal Program for Scientific Translations, Jerusalem. Pp. 1-538.

Nikol'skii, G.V. 1956. Ryby basseina Amura [Fishes of the Amur Basin], Moscow, USSR Academy of Sciences. Pp. 551[In Russian]*

Odenkirk, J. and S. Owens. 2005. Northern snakehead in the tidal Potomac River system. Transactions of the American Fisheries Society 134: 1605-1609.

Odenkirk, J. and S. Owens. 2007. Expansion of a northern snakehead population in the Potomac River system. Transactions of the American Fisheries Society 136: 1633-1639.

Odenkirk. J., C. Lim, S. Owens & M. Isel. 2013. Insight into Age and Growth of Northern Snakehead in the Potomac River, North American Journal of Fisheries Management, 33:4, 773-776, DOI: 10.1080/02755947.2013.806382

Odenkirk, J. VDGIF (Virginia Department of Game and Inland Fisheries), personal communication, 2012

Okada, Y. 1960. Studies of freshwater fishes in Japan, II, Special part: Prefectural University of Mie, Journal of the Faculty of Fisheries 4(3):1-860, 61 plates.

Oliver, M., Arkansas Game and Fish Commission, personal communication, 2014
Orrell, T.M., and L. Weigt. 2005. The northern snakehead *Channa argus* (Anabantomorpha: Channidae), a non-indigenous fish species in the Potomac River, U.S.A. Proceedings of the Biological Society of Washington 118(2): 407-415.

Pasko S and J. Goldberg. 2013. Evaluating Harvest Incentives to Control Invasive Species Manuscript submitted for publication.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres, Jr. 1998. Fishing down marine food webs. Science 279:860-863.

PFBC (Pennsylvania Fish and Boat Commission) Press Release. July 23, 2004. Another exotic species confirmed in Pennsylvania waters.
http://sites.state.pa.us/PA_Exec/Fish_Boat/newsreleases/2004/snakehead.htm

Pethiyagoda, R. 1991. Freshwater fishes of Sri Lanka. Wildlife Heritage Trust of Sri Lanka: Columbo. Pp. 1-362.*

Phillips SJ, Anderson RP, Schapire RE. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling 190(3–4): 231–259

Pimentel, D., R. Zuniga, and D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the U.S.. Ecological Economics. 52: 273-288.

Poulos, H.M, B. Chernoff, P.L. Fuller, and D. Butman. 2012. Ensemble forecasting of potential habitat for three invasive fishes. Aquatic Invasions 7:59-72.

Roberts, T.R. 1989. The freshwater fishes of western Borneo (Kalimantan Barat, Indonesia): Memoirs of the California Academy of Sciences 14, 210 p.

Saylor, R.K., N.W. Lapointe, and P.L. Angermeier. 2012. Diet of non-native northern snakehead (*Channa argus*) compared to three co-occurring predators in the lower Potomac River, USA. Ecology of Freshwater Fish, in press.

Schmidt, J. 2001. Asian snakehead, genus *Channa*. Tropical Fish Hobbyist 6:62-73.

Scholkopf B, Platt JC, Shawe-Taylor J, Smola AJ, Williamson RC. 2001. Estimating the support of a high-dimensional distribution. Neural Computation 13: 1443–1471.

Secor, D.H. 1999. Longevity and resilience of Chesapeake Bay striped bass. Journal of Marine Science 57: 808-815.

Severinghaus, L. and L. Chi. 1999. Prayer animal release in Taiwan. Biological Conservation 89: 301-304.

Sifa, L. and Senlin, X. 1995. Culture and capture of fish in Chinese reservoirs: Ottawa, Canada, International Development Research Center, 128 p.*

Stockwell, D.R.B. and Peters, D., 1999. The GARP Modeling System: problems and solutions to automated spatial prediction. Int. J. Geographical Inf. Sci., 13 (1999), pp. 143–158.

Surprenant, L. NYDEC (New York Department of Environmental Conservation), personal Communication, 2013.

Talwar, P.K., and A.G. Jhingran, 1992. Inland fishes of India and adjacent countries. Vol. 2. Balkema Publishers: Rotterdam. Pp. 543-1158.*

Thomsen, P.F., J. Kielgast, L.L. Iversen, C. Wiuf, M. Rasmussen, M.T.P. Gilbert, L. Orlando, and E. Willerslev. 2012. Monitoring endangered freshwater biodiversity by environmental DNA. Molecular Ecology 21:2565-2573.

Uchida, K. and M. Fujimoto. 1933. Life history and method of culture of the Corean snake-head fish, *Ophiocephalus argus*. Bull. Fish. Exp. Stn. Gov. Gen. of Chosen, Fusan, 3:1-91.

U.S. Senate. Committee on Appropriations. *Department of the Interior and Related Agencies Appropriations Bill.* (S.Rept.108-341). Washington: Government Printing Office, 2005.

U.S. Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. 2006. National Survey of Fishing, Hunting, and Wildlife Associated Recreation.

USFWS (U.S. Fish and Wildlife Service). 2002. 50 CFR part 16. RIN 1018-AI36. Injurious Wildlife Species; Snakehead (family Channidae) Proposed Rule. http://www.eswr.com/f072602.txt

USFWS (U.S. Fish and Wildlife Service). 2011. Brooklyn trading company owner charged with illegally importing live snakehead fish. Press Release April 28, 2011. http://www.fws.gov/northeast/le/snakeheadarrest.html

USFWS (U.S. Fish and Wildlife Service). unpublished data, 2012

USGS (U.S. Geological Survey), September 2013

Vander Zanden, M.J. and J.D. Olden. 2008. A management framework for preventing the secondary spread of aquatic invasive species. Canadian Journal of Fisheries and Aquatic Sciences 65:1512-1522.

Wee, K. L. 1982. Snakehead-Their biology and culture, *in* Muir, J.F. and R.J. Roberts, eds. Recent advances in aquaculture: Boulder, Colorado, Westview Press, p. 180-213.

Wilson, L. NYDEC (New York Department of Environmental Conservation), personal Communication, 2012.

Worrall, J. 2002. Review of systems for early detection and rapid response. Unpublished report to the National Invasive Species Council, Washington, D.C., USA.

Appendix C. Information Access and Data Management

Information access and data management are important components of a species management plan. To effectively manage aquatic invasive species like snakehead, fish and wildlife managers need information on their biology, distribution, effective control methods, state and federal management regulations, and education and outreach materials.

Several data collection systems have been developed, but the information is not universally available, regularly updated, or consistent. A national level database for access by researchers, managers and even the public is needed. Several have been developed but need a lead manager and funding to make the information useable. Current information systems that collect snakehead data include:

- BugwoodApps are available for iOS and Android systems and enable users to have access to electronic field guides and to report sightings of invasive species with their smartphone. Georeferenced reports with images are incorporated into EDDMapS;
- Early Detection and Distribution Mapping System (EDDMapS) is a web based mapping system for documenting invasive species distribution by the Center for Invasive Species and Ecosystem Health at the University of Georgia. EDDMapS combines data from other databases, organizations and citizen scientists to create a national network of invasive species distribution data. Users enter observation information and images into the standardized web form or with regional smartphones apps. All data are reviewed by state verifiers to ensure all data is accurate. The data are made available to scientists, researchers, land managers, landowners, educators, conservationists, ecologists, farmers, foresters, state and national parks, www.eddmaps.org;
- FishBase is a global relational database with information on practically all fish species known to science to cater to different professionals such as research scientists, fisheries managers, zoologists and many more, (http://www.fishbase.org/search.php);
- Global Registry of Invasive Species Database, (GISD), collects information on worldwide invasive alien species that threaten native biodiversity and covers all taxonomic groups from micro-organisms to animals and plants in all ecosystems, http://www.issg.org/database/welcome/;
- Great Lakes and Mississippi River Interbasin Study, (GLMRIS), has developed an inventory of available control methods for ANS of concern, http://glmris.anl.gov/index.cfm;
- Great Lakes Restoration Initiative, (GLRI), database tracks the progress of projects that prevent the introduction of new invasive species and provides an invasive species risk assessment database, http://greatlakesrestoration.us/index.html;
- Invasive Species Compendium, (CABI) is a constantly developing encyclopedic resource containing datasheets on over 1500 invasive species and animal diseases, basic datasheets on further species, countries, habitats and pathways, and

bibliographic database of over 75,000 records (updated weekly), http://www.cabi.org/isc/;

- Mid Atlantic Early Detection Network (MAEDN) is the result of a cooperative effort between the National Park Service (National Capital Region, Integrated Pest Management and Invasive Species Program) and the University of Georgia's Center for Invasive Species and Ecosystem Health (CISEH) and utilizes their widely used Early Detection Distribution Mapping System (EDDMapS) to report highly invasive and early detection invasive plant species. Snakehead and other species will continue to be added as appropriate. http://apps.bugwood.org/mid_atlantic.html
- National Exotic Marine and Estuarine Species Information System, (NEMESIS), relational database compiles detailed information on approximately 500 different non-native species of plants, fish, invertebrates, protists and algae that have invaded coastal U.S. waters. The database identifies which species have been reported, their current population status (i.e., whether established or not), as well as when, where, and how they invaded; it also summarizes key information on the biology, ecology, and known impacts of each invader, http://invasions.si.edu/nemesis/databases.html;
- Northeast Aquatic Nuisance Species, (NEANS), Online Guide provides information about invasive species that threaten northeastern North America to allow the creation of customized field guides, http://www.northeastans.org/online-guide/;
- PetWatch provides consumers with a science-based list of the Best, Fair and Worst choices of exotic pets based on extensive research aimed at protecting native wildlife and resources, global biodiversity and public health, http://www.petwatch.net/browse_animals/;
- USDA National Invasive Species Information Center is a reference gateway to information, organizations, and services about invasive species including summaries of state laws and regulations, http://www.invasivespeciesinfo.gov/laws/statelaws.shtml;
- USFWS Law Enforcement Management Information System, (LEMIS), investigative case tracking system collects AIS information (link available to authorized USFWS personnel); and
- U.S. Geological Survey' Non-indigenous Aquatic Species database (USGS NAS) is a national database providing real-time occurrence data within the U.S. of non-indigenous aquatic species observations and collections, http://nas.er.usgs.gov/.

All of these databases have valuable features but there is no single centralized database that provides all the information needed to manage AIS. It would be valuable to have one central location for the information.

Appendix D. Rotenone Label and MSDS