Invasive Goldfish

Carassius auratus (Linnaeus, 1758)

Background

The Goldfish *Carassius auratus* (Linnaeus, 1758) has an ambiguous origin. Historical records suggest they are likely the descendants of the Crucian Carp *Carassius carassius* (Linnaeus, 1758) native to Europe and Siberia and domesticated for food in China 2,000 years ago (Chen *et al*. 2020). Today, Crucian Carp, sometimes called “wild Goldfish”, can still interbreed with Goldfish, though they display morphological differences. Most Crucian Carps are a golden bronze color, while feral Goldfish revert to silver or olive green within a few generations. Goldfish are also smaller, at around 12-22cm, compared to the Crucian Carp’s 50cm, and have a more pointed snout (Nico *et al.* 2022). Figures 1 and 2 show the differences between a wild-type Goldfish and Crucian Carp.

At some point, sudden genetic changes (due to random mutations or hybridization with other carp species) occurred in some domesticated Crucian Carp in China, inhibiting gray pigment cells and allowing red and yellow pigments, present in smaller quantities, to express themselves (Chen 1956; Wang *et al.* 2014). The earliest documented occurrence of red scales dates to the Jin Dynasty (AD 265 to 420) (Chen *et al.* 2020). These mutated, colorful Crucian Carps were selectively bred over thousands of years into the hundreds of breeds of Goldfish recognized in China today. Brightly colored fish held cultural significance in ancient China, and Goldfish were particularly admired for their mystical ability to transform from earth-toned fry to vibrant adults. Records show that a Song Dynasty (AD 960 to 1279) empress had an imperial pond built for her yellow Goldfish and banned commoners from keeping them, as yellow was the color of royalty (Roos 2019). Goldfish continue to hold cultural significance in modern times, though their status as a commodity has greatly diminished along with their rarity. Today, Common Goldfish are regularly used as fishing bait and live feed for carnivorous aquarium fish across the world. Their popularity as pets and the continuous breeding of "fancy" Goldfish varieties has sustained the species as an item of global economic and ecological importance (Nico *et al.* 2022).

Transportation and Introduction

In 1868, Charles Darwin wrote on Goldfish, "Passing over an almost infinite diversity of color, we meet with the most extraordinary modifications of structure" (Darwin 1868). He recorded triple tails, double fins, no fins, humped backs, "globular" forms, and "enormously large and protuberant" eyes. From the standard Common Goldfish to the humped Ryukin to the long-tailed Veiltail and bubbly-headed Ranchu, the exotic variety of breeds makes the Goldfish a popular ornamental species around the world. Though some Goldfish do enter new waterways as discarded bait fish, the main invasion vector for Goldfish is the ornamental fish trade.

Goldfish first spread across China during the Jin (AD 265 to 420), Tang (AD 618 to 907), and Song (AD 960 to 1279) Dynasties as garden pool ornaments. As the Goldfish spread, Chinese breeders brought out new colors and the first "fancy" tails. Ornamental Goldfish were introduced to Japan sometime in the 16th or 17th century, where the Tosakin and Ryukin breeds eventually emerged. Goldfish were introduced to Europe in the 17th century, where they are thought to have spread out from Portugal (Chen *et al.* 2020). Records show that they were frequently kept by collectors and the upper classes for a short time before interest waned with increasing availability (Roos 2019). It is unclear when the Goldfish was first introduced to the U.S., but numbers began to pick up in the late 1870s when the U.S. Fish Commission (a federal agency later absorbed by the U.S. Fish and Wildlife Service) began breeding and distributing Goldfish around the country. (Nico *et al.* 2022). Today, the ever-present demand for both the common Goldfish and its fancy spin-offs means that pet releases and escapees from overflowing ponds will continue to be a matter of concern for the foreseeable future.

Establishment

Repeated introductions, coupled with their adaptability and generalist tendencies, have made the Goldfish a very successful species (Lorenzoni *et al.* 2007). Goldfish can tolerate high water turbidity, low oxygen availability, and a broad range of temperatures (0.3˚ C to 43.6˚ C), salinities (up to 17 ppt), and pH levels (4.5 to 10.5) (Jacquin *et al.* 2019; Schofield *et al.* 2006; Nico *et al.* 2022). This allows them to establish in a wide variety of freshwater habitats, including lakes, streams, ponds, and swamps. They are also omnivorous, with a diet including benthic vegetation, detritus, phytoplankton, planktonic crustaceans, insects, fish eggs, and fry (Tarkan *et al.* 2010). Their bottom-feeding behavior kicks up benthic sediment, resuspending nutrients and decreasing water transparency. Since Goldfish are more tolerant of turbidity than many other species, this environmental change may give them a competitive advantage that allows them to establish despite the presence of predators and competitors (Jacquin *et al.* 2019; Schofield, Brown and Fuller 2006).

Goldfish (especially brightly colored Goldfish) are susceptible to predation from birds, humans, and other fishes. Under the pressure of selective predation, feral Goldfish populations usually revert to the wild-type olive coloration within a few generations and lose this vulnerability (Nico *et al.* 2022). The Goldfish's high fecundity and ability for gynogenesis further protects establishing populations from the effects of predation and demographic stochasticity (Lorenzoni *et al.* 2007). The presence of predators and competitors in introduced Goldfish populations has also been correlated with increased physical growth. This allows the Goldfish to rapidly reach a "safe" size, gaining protection from predators earlier in life

(Lorenzoni *et al.* 2007). A larger body size, though sometimes coupled with reproductive tradeoffs such as smaller egg diameter, may also help them compete for resources against congeners like the Crucian Carp, which seek to fill similar ecological roles (Tarkan *et al*. 2010).

Goldfish share their habitats with Crucian Carp in many places around the world. In the U.K., the invasive Goldfish threatens the ponds of native Crucian Carp, while both cyprinids are invasive in Australia (Gwilym *et al*. 2012; Tarkan *et al*. 2010). Although the two species often find themselves in competition, they can also interbreed, and hybridization and introgression between the two can lead to the exchange of useful alleles. For example, Goldfish, which are resistant to the Koi herpes virus (suggested as a possible biotic control against Crucian Carp in Australia), may be able to pass that resistance to Crucian Carp hybrids. Through this gene flow, both species increase their genetic diversity and establishment success (Gwilym *et al.* 2012).

Spread

The Goldfish is a highly successful nonnative, with wild occurrences documented in every U.S. state and on all continents except Antarctica (Figures 3 and 4). Though Goldfish are frequently spread through translocation by humans, they can also increase their range by natural dispersal through interconnected waterways (Lorenzoni *et al.* 2007). As with establishment, the Goldfish's hardiness and ability to adapt to a variety of biotic and abiotic conditions have been instrumental in its spread around the world.

Two factors that limit Goldfish spread are water temperature and nutrient availability. In their preferred warm, nutrient-rich environments, Goldfish take advantage of the ideal conditions to develop large bodies and high fecundity (as measured by the total number of eggs in the ovaries of an adult female). On the other hand, Goldfish in environments with extreme seasonal temperature fluctuations or low nutrient availability often have smaller bodies and low fecundity. Low water availability or low dissolved oxygen content may also decrease fecundity and constrain population size (Yintao *et al.* 2019). Although "warm water, high nutrients" is their general preference, Goldfish can successfully spread to colder, nutrient-poor climates (Jacquin *et al.* 2019). For example, an invasive population at high elevations on the Tibetan Plateau in China has shown a decreased egg diameter, increased fecundity, prolonged growth period, and increased body length. In cold climates where nutrient availability is low, the competitive advantages of a large body size may be worth delaying maturity, while smaller eggs with a shorter incubation period may make better use of the shortened windows of seasonal nutrient availability. Trade-offs and adjustments between reproduction and growth traits are common among Goldfish dispersed across nonideal environments and may represent another adaptation that has allowed the species to proliferate outside of its usual bounds (Yintao *et al.* 2019).

Human activities that alter the temperature and composition of habitats may also impact the reproduction, growth, and spread of Goldfish. For example, phosphorus and nitrogen fertilizers entering lakes from agricultural runoff can raise the water's nutrient supply and allow for the development of bigger, more reproductively successful Goldfish (Yintao *et al.* 2019). On the other hand, Goldfish populations may be limited by exposure to pesticide pollutants that can cause irreversible gill and liver damage (Jacquin *et al.* 2019). There has also been concern that anthropogenic climate change, which may raise more waters toward the Goldfish's preferred temperature of 22˚ C, may open new habitats to invasion (Lorenzoni *et al.* 2007).

Impacts

The international Goldfish trade acts as a vector for the co-introduction of Goldfish parasites that can jump hosts to other fish and amphibian species. Out of the 197 parasites known to infect Goldfish, at least 26 are believed to have coinvaded. The parasites *Ichthyophthirius multifiliis*, *Argulus japonicus,* and *Lernaea cyprinacea* are of particular concern due to their low host specificity and adaptable life cycles. Transmission of these parasites to farmed freshwater fish could result in significant economic losses. Goldfish also carry myxozoans and monogeneans, which are difficult to detect and can lead to death or severe disfigurement for many aquarium species. Without early detection and quarantine, myxozoans and monogeneans can significantly impact aquarium businesses, which rely on the aesthetic value of their fish (Trujillo-González, Becker and Hutson 2018). The transmission of Goldfish parasites to wild species is similarly of ecological concern.

In the wild, invasive Goldfish reduce the populations of other species by grazing on aquatic plants and preying on native and nonnative amphibians, insects, crustaceans, mollusks, annelids, and fish (Van der Veer and Nentwig 2014; Richardson *et al.* 1995). Their foraging behavior (which involves sucking up a mouthful of benthos, spitting it out in a cloud, and picking out the edible bits) also uproots plants, resuspends nutrients, and increases water turbidity. As mentioned before, this can reduce the success of the Goldfish's predators and competitors, which are often not adapted to hunting and foraging in cloudy water. Turbidity can also lead to changes on an ecosystem level. For example, cloudy water shortens the penetration depth of incoming sunlight, causing heat to concentrate near the surface (Kirk 1985). The warm surface water, coupled with the suspended nutrients, can lead to phytoplankton blooms that further decrease water transparency. Meanwhile, the lack of sunlight in deeper water reduces energy availability and community productivity in those regions. Creating these cool, deep refuges can be advantageous to Goldfish, allowing them to survive summers in shallow pools that would otherwise reach temperatures above their habitable range (Richardson 1995).

Management

Through early detection and rapid response, a small number of goldfish can be eradicated through physical removal (by electrofishing, for example). Once a population has established, however, eradication becomes difficult or impossible. Due to their hardiness, Goldfish are resistant to many conventional management methods. Because Goldfish have a higher chemical tolerance than many other fishes, piscicides like Antimycin A and rotenone are unable to target them without indiscriminately killing many native species (Clearwater, Hickey and Martin 2008). Another solution, which involves anaesthetizing the fish by pumping carbon dioxide into the water and removing Goldfish by hand, has only limited success due to the Goldfish's comparatively high tolerance of hypoxic conditions (Roesner *et al.* 2008).

An important concern in Goldfish management is the prevention of parasite cointroductions. Treatment, quarantine, and inspection of translocated Goldfish can help to deter parasites from crossing borders. Because parasites frequently hide inside the skin, fins, or gills of Goldfish and are impossible to detect during certain life stages, quarantine times should be informed by the parasites' life cycles and reflect these periods of uncertainty (Wafer 2015; Zhou *et al.* 2020). Environmental DNA tests on the water that Goldfish are transported in can also give an idea of their parasite profile, although this technology is not yet reliable without extensive validation (Trujillo-González 2018).

The most effective strategy for managing Goldfish is preventing introductions. Education and outreach to pet owners, businesses, and others involved in the movement of Goldfish can encourage people to practice more care in handling them (by refraining from releasing unwanted pets or stocking Goldfish in ponds with a great flood risk, for example). One vector for introduction that has seen recent attention is the Buddhist tradition of “fang sheng”, or mercy release. This ritual freeing of captive animals dates back to antiquity and often involves the release of Goldfish into wild waters (Shiu and Stokes 2008). In 1997, the New York Times reported the ritual release of 2,500 such Goldfish into Westons Mill Pond in New Jersey (Everard *et al*. 2019). The fang sheng of Goldfish has undocumented but likely significant impacts on their establishment and spread. Since fang sheng is a tradition grounded in compassion and protection, raising awareness on the unintentional harm done through Goldfish releases can encourage people to choose native animals for release and prevent the introductions of nonnative Goldfish.

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Figure 1. Goldfish with slightly pointed snout and olive coloring (Nico *et al.* 2022).

Figure 2. Crucian Carp with rounded snout and bronze coloring (Schofield, Nico and Fuller 2022).

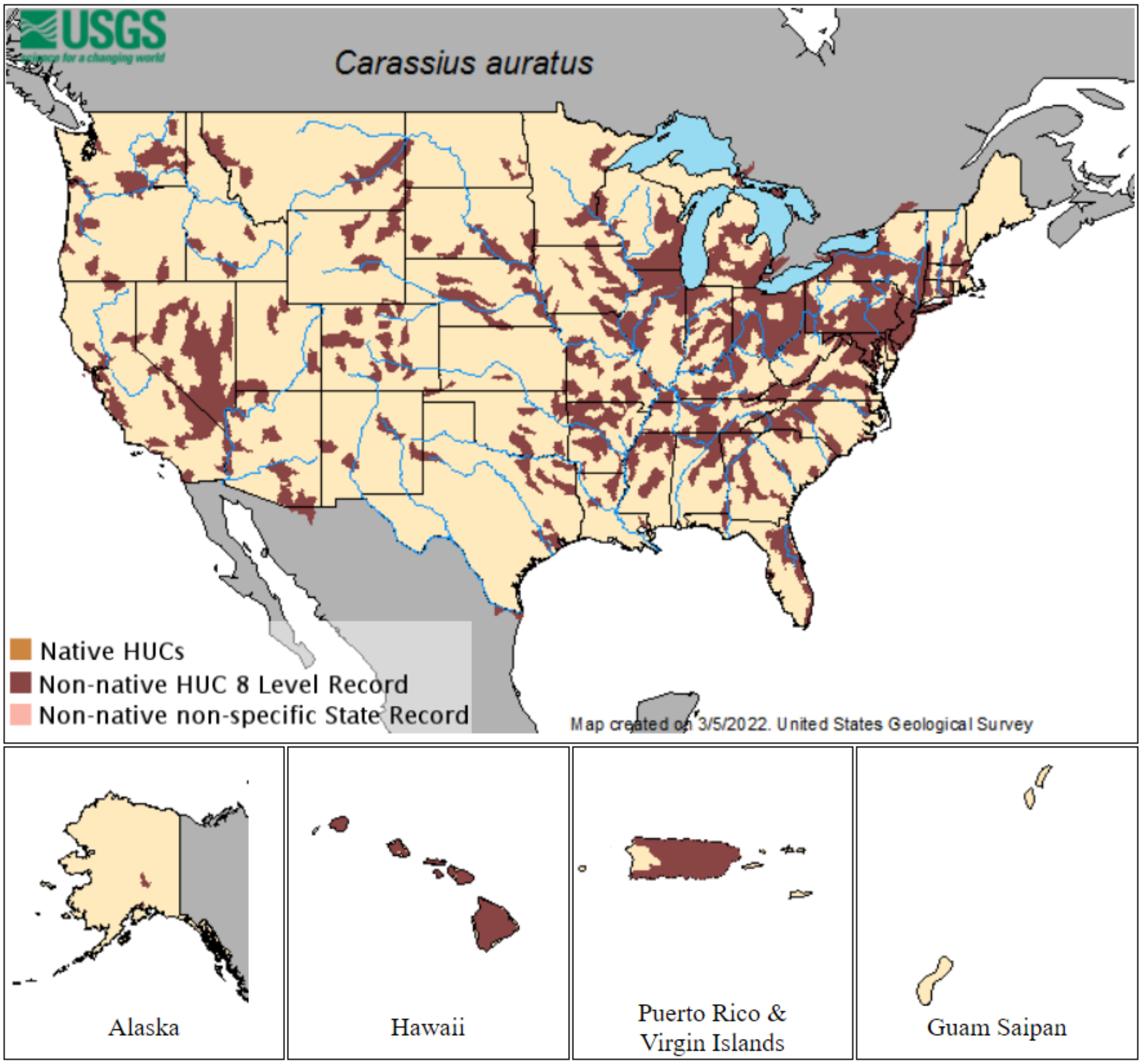

Figure 3. U.S. range of Goldfish (Nico *et al.* 2022).

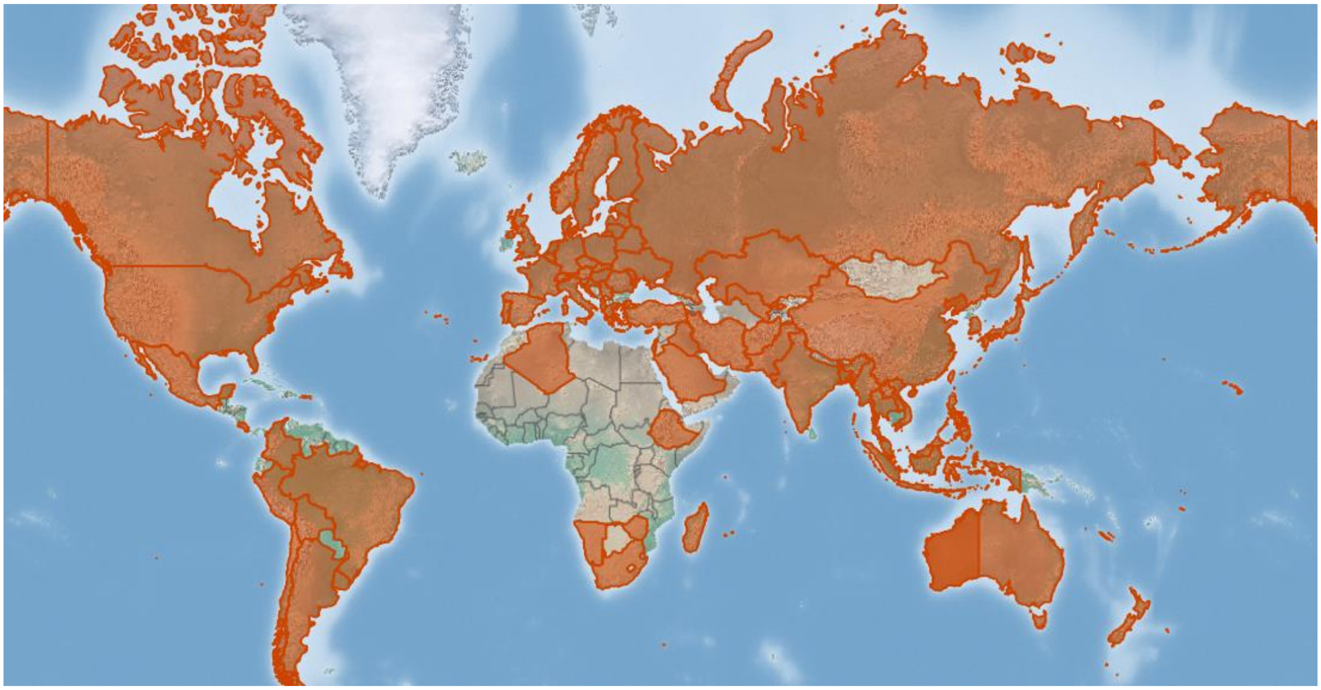

Figure 4. Global range of Goldfish (Siriwardena 2010).