1 Why Propagate Freshwater Mussels?

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1.1 GLOBAL CONSERVATION STATUS

Freshwater mussels have successfully colonized every continent on Earth except Antarctica (Bogan, 2008); yet, nearly half of the global freshwater mussel species are listed as imperiled (IUCN, 2016). Without concerted efforts toward conservation, Ricciardi and Rasmussen (1999) project that 127 freshwater mussel species could go extinct by 2099. In North America, 74% of the known 300 species are imperiled, 220 of which are listed as endangered, threatened or of special concern in the United States, and at least 35 species are considered extinct (Williams *et al.*, 1993; Neves *et al.*, 1997) (Figure 1.1). Of the 16 species recognized in Europe, 3 are critically endangered, 2 are vulnerable, and 5 species are near threatened (Lopes-Lima *et al.*, 2017). Indeed, all European *Margaritifera* species are listed as "fauna requiring special measures to be taken for their protection" under the provisions of the Bern Convention on the Conservation of European Wildlife and Natural Habitats. Bauer (1986) reported that southern Europe's freshwater pearl mussel (*Margaritifera margaritifera*) had declined markedly with only 2 of the 12 rivers supporting stable populations. Freshwater pearl mussel populations in Russia follow a similar trend, with 70% of historic populations in southern Russia likely extirpated (Popov and Ostrovsky, 2014). Geist (2010) cautions that an ongoing lack of recruitment may lead to further declines in Europe's freshwater mussel populations. The conservation status of freshwater mussels in South America is less well known, but many species are declining (Pereira *et al.*, 2014). Ninety-three percent of the freshwater bivalves in Uruguay are priorities for conservation

FIGURE 1.1 The clubshell (*Pleurobema clava*) collected from the Allegheny River (Forest County, Pennsylvania). The clubshell is listed as federally endangered in the United States under the Endangered Species Act of 1973.
Photo: Ryan Hagerty, USFWS.

(Clavijo *et al.*, 2010). One percent of Brazil's freshwater bivalves are listed as critically endangered, 10% endangered, 9% vulnerable, and 37% are in need of further evaluation for potential listing (Pereira *et al.*, 2012). One species is listed as vulnerable in Columbia (Ardila *et al.*, 2002) and eight species are listed as endangered by the Ministerio de Agricultura Ganaderia in Paraguay. There also are data gaps in our knowledge of freshwater mussels in Africa and Australasia (Seddon *et al.*, 2011, Walker *et al.*, 2014). Seddon *et al.* (2011) estimates that 25% of the species in Africa are extinct, critically endangered, endangered, vulnerable, or near threatened, and an additional 25% are lacking sufficient data to assess their status. Of the 32 species found in Australasia, 7 are listed by the International Union for the Conservation of Nature or under national or state legislation, and Walker *et al.* (2014) believe that a much-needed systematic revision

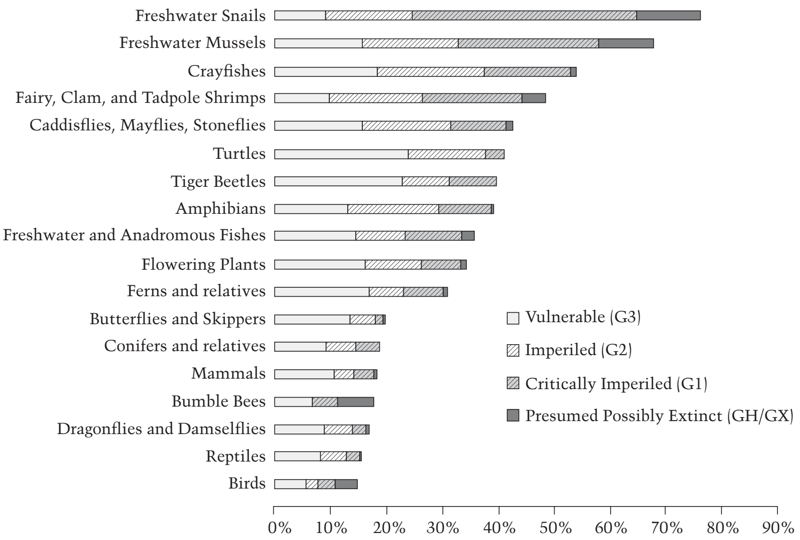

FIGURE 1.2 Percentage of species listed as vulnerable, imperiled, critically imperiled, and presumed possibly extinct by faunal and floral group in North America. The figure clearly shows that freshwater species are more imperiled than their terrestrial counterparts. Graphic courtesy of NatureServe and adapted by Kristin Simanek, USFWS.

will likely increase this number. Little or no information is available on the conservation status of freshwater mussels in China. In 2008, however, the Ministry of Environmental Protection categorized 45% of the major river reaches as either moderately or badly polluted, with all freshwater fishes eliminated from a full 5% of the length of Chinese rivers as a direct result of pollution (Dudgeon, 1999). It is likely, therefore, that impacts on freshwater mussels in China are similar to other parts of the world.

Mussels are certainly not the only imperiled group of animals in freshwater ecosystems (Figure 1.2). Strayer (2006) estimates that approximately 12 000 species of freshwater invertebrates are either extinct or imperiled globally. Of the 703 freshwater snail species (Gastropoda) in the United States and Canada, 74% are listed as vulnerable, threatened or endangered and 67 species are considered extinct or possibly extinct (Johnson *et al.*, 2013). Richman *et al.* (2015) estimate that 32% of the nearly 600 species of crayfish worldwide are in danger of extinction. In the United States and Canada, 174 of the 363 crayfish species (48%) are listed as endangered, possibly extinct, threatened or vulnerable (Taylor *et al.*, 2007). Freshwater vertebrates are not immune to these declines. Between 1898 and 2006, 57 species of freshwater fishes in North America went extinct (Burkhead, 2012). Of the remaining 700 species of fishes in North America, 39% are listed as imperiled (Jelks *et al.*, 2008). The global conservation status of freshwater fishes is more difficult to assess due to significant data gaps. Only about 5800 of the 15 570 described freshwater fish species (37%) had been assessed as of 2011, with 30% of the 5800 listed as extinct, extinct in the wild or threatened with extinction (Carrizo *et al.*, 2013). These statistics paint a clear picture that freshwater systems in North America and around the world are in trouble. In fact, extinction rates in freshwater ecosystems appear to be five times higher than extinction rates in terrestrial systems and even rival extinction rates for the tropical rainforests (Ricciardi and Rasmussen, 1999).

1.2 CAUSES OF THE DECLINE

As with most imperiled species, it can be difficult to point to a single cause for the decline of freshwater mussel populations. Authors from around the world have cited similar impacts to freshwater mussel populations, from habitat loss and alteration, commercial harvest, pollution, loss of fish hosts, to competition with invasive species (Bauer, 1988; Lydeard *et al.*, 2004; Strayer *et al.*, 2004; Nobles and Zhang, 2011; Haag, 2012; Lopes-Lima *et al.*, 2014; Pereira *et al.*, 2014). Downing *et al.* (2010), however, found few research papers that provided evidence of a direct causal link between mussel declines and any specific impact. The most frequently cited cause for the decline of freshwater mussel populations, and numerous other faunal groups around the world, is habitat loss. Human activity has left very few rivers on Earth unimpacted (Vorosmarty *et al.*, 2010). The construction of nearly 1 million dams globally (Jackson *et al.*, 2001) has resulted in the loss of many natural, free-flowing river segments, negatively impacting flow rates, sediment loads, temperature regimes, and dissolved oxygen upstream and downstream of the dams. In North America, only 40 river segments larger than 200 km (125 miles) in length are still free-flowing (Benke, 1990). By the mid-1940s, the upper Mississippi River and the entire length of the Tennessee River were controlled by dams (Etnier and Starnes, 1993; Anfinson, 2003). One stark example of the impacts of impoundments on freshwater mussels comes from Fort Loudoun Reservoir on the Tennessee River. Prior to impoundment, this stretch of the Tennessee River supported 64 species of freshwater mussels (Ortmann, 1918). After impoundment, only 4 species remained (Isom, 1971). Impoundments can be tied directly to the extinction of at least 12 species of freshwater mussels (Haag, 2012).

Beginning in the 1960s, however, mussel populations began to decline in unimpounded and seemingly healthy streams (Haag, 2012). The Embarrass River, for example, experienced an 86% decline in the freshwater mussel fauna, despite the river being classified as one of Illinois' outstanding streams (Cummings *et al.*, 1988). Crashes to other local mussel faunas were documented all over the United States, including the states of Georgia, Iowa, Kansas, Kentucky, Michigan, Tennessee, Texas, and Virginia (Distler and Bleam, 1995; Howells *et al.*, 1997; Evans, 2001; Haag and Warren, 2004; Poole and Downing, 2004; Hanlon *et al.*, 2009; Morowski *et al.*, 2009; Jones *et al.*, 2014). While many of these rivers support healthy assemblages of fishes and aquatic insects, extant mussel populations are comprised almost entirely of old, relict individuals (Haag, 2012; Strayer and Malcom, 2012). Lack of recruitment had led to the disappearance of short-lived species followed by a gradual decline of the longer-lived species (Haag, 2012). Strayer and Malcom (2012) were interested in identifying possible causes for mussel recruitment failure in rivers in southeastern New York. They found no relationship between recruitment failures and fine sediment, interstitial oxygen concentration, fish host abundance, or crayfish predator abundance. They did, however, show that concentrations of un-ionized ammonia greater than 0.2 mg N/L in the interstitial water were correlated with recruitment failure. Recent laboratory research also has shown that the juvenile life stage of freshwater mussels is highly susceptible to environmental contaminants. In fact, juvenile mussels may be an order of magnitude more susceptible than the standard test organisms used by the United States Environmental Protection Agency for contaminants like ammonia and copper (Wang *et al.*, 2007a, 2007b). Additional research is needed to better understand the causes of these freshwater mussel declines. If the causes are not identified and ameliorated, recovery efforts are likely to fail.

1.3 ECOLOGICAL SIGNIFICANCE OF FRESHWATER MUSSELS

Healthy freshwater mussel beds can make up 50–90% of the benthic biomass in streams, in some cases exceeding the biomass of all other benthic species combined by an order of magnitude (Negus, 1966; Layzer *et al.*, 1993; Strayer *et al.*, 1999). Because an organism's (or group of organisms') contribution to ecological processes is directly proportional to their biomass (Strayer *et al.*, 1999; Vaughn *et al.*, 2004), the severe decline in mussel populations described above is likely having a significant impact on freshwater ecosystems. Indeed, a growing understanding of the ecology and physiology of freshwater mussels indicates they play a significant role in structuring food webs and providing ecological functions important to maintaining the overall health of the ecosystem (Zimmerman and Szalay, 2007; Vaughn, 2010; Allen and Vaughn, 2011; Allen *et al.*, 2012; Atkinson *et al.*, 2013, 2014a; Strayer, 2014; Atkinson and Vaughn, 2015). For example, freshwater mussels, like many marine bivalves, are extremely efficient filter feeders. Large mussel beds are capable of filtering the entire volume of water passing over the bed at any given time (Welker and Walz, 1998; Vaughan *et al.*, 2004). Exponential declines in phytoplankton biomass in the River Spree in Germany were attributed to filtration by dense freshwater mussel beds (350 mussels/m^2; Welker and Walz, 1998). Additionally, as mussels convert filtered organic material into excretory products, nutrients are transferred from the water column to the benthos (Spooner and Vaughn, 2006). Where nutrients are limiting, mussel excreta can support the rest of the food web, leading to increases in benthic algae, macroinvertebrates, and fish (Allen *et al.*, 2013; Atkinson *et al.*, 2014b). In the Kiamichi River in southeastern Oklahoma, benthic areas around live mussel beds had higher invertebrate abundance and organic matter concentrations than areas of the river with no mussels (Spooner and Vaughn, 2006). Mussel-provided nutrients also can alter algal composition, decreasing blue-green algae and increasing water quality (Atkinson *et al.*, 2013). The burrowing behavior of freshwater mussels can increase water and oxygen penetration through the sediment, as well as release nutrients from sediments and stabilize river substrates (Matisoff *et al.*, 1985; McCall *et al.*, 1995; Zimmerman and de Szalay, 2007; Allen and Vaughn, 2011). Live mussels also are an important food resource for fishes, mammals, and birds, and dead shells are a source of calcium as well as habitat for some aquatic organisms (Vaughn, 2010). Finally, intact mussel assemblages can improve conditions for rare species (Spooner and Vaughn, 2009).

1.4 RECOVERY EFFORTS

The high level of imperilment in global freshwater mussel populations combined with their important function as "ecosystem engineers" is causing great concern among scientists, prompting the creation of freshwater mussel conservation programs around the world (Lydeard *et al.*, 2004; Strayer *et al.*, 2004). This book is designed to introduce the reader to one aspect of these multi-faceted conservation programs, the propagation and stocking of freshwater mussels.

As early as 1899, biologists with the United States Bureau of Fisheries' Fairport Biological Station began developing mussel propagation techniques to supplement populations declining as a result of harvest for the pearl button industry (Pritchard, 2001). After extensive work on host fish relationships and juvenile mussel culture, the Fairport Station closed in 1933. In the 1960s, widespread reports of dramatic declines in freshwater mussel populations renewed research into mussel propagation technology. This new research has resulted in vast improvements in life history information and rearing practices, as well as the development of mussel propagation programs in the United States, Europe, and other countries (Hastie and Young, 2003; Neves, 2004; Thomas *et al.*, 2010; Haag and Williams, 2014). In the United States, the primary goal has been species recovery. Management objectives in many Endangered Species Recovery Plans and State Wildlife Action Plans include restoring viable populations to a significant portion of the species historic range, restoring resilience to environmental impacts, and preventing new species from being listed under the Endangered Species Act of 1973. Several propagation programs also are working to restore mussel beds impacted by chemical spills or other instream activities, like bridge replacements (Morrison *et al.*, 2013; Lane *et al.*, 2014). There is a growing demand, however, for propagation programs aimed at restoring complete mussel assemblages, including both common and rare species. Restoring the ecosystem goods and services provided by freshwater mussel beds is likely fundamental to the long-term viability of mussel populations (Vaughn and Spooner, 2006). In fact, endangered species recovery efforts will likely be more successful if the complete mussel assemblage is restored (Haag, 2012). Mussel propagation facilities also are frequently tasked with producing mussels for research and serving as centers for holding captive populations of species on the brink of extinction (i.e. ark populations). Finally, propagation facilities provide an ideal environment to inform the public about the importance of freshwater mussels.

Restoring mussel habitat and improving water quality also must be key elements to any multi-faceted conservation effort. Unfortunately, once populations have declined, it can take decades for freshwater mussels to recolonize restored habitat, due to their complex life history. Consequently, propagation programs are oftentimes necessary to prevent extinction prior to habitat restoration or to jump-start species recovery after the habitat is restored. As a result, propagation is likely to remain a key conservation management strategy for restoration and recovery of freshwater mussels into the future. Propagation of freshwater mussels, however, should not be taken lightly and any facility that is considering starting a propagation program should carefully consider the following questions.

1.5 QUESTIONS TO CONSIDER BEFORE STARTING A FRESHWATER MUSSEL PROPAGATION PROGRAM

1.5.1 *Why Are We Propagating Freshwater Mussels and is Propagation the Best Restoration Strategy?*

The first question to answer before starting a mussel propagation program is "Why are we propagating freshwater mussels and is propagation the best restoration strategy?" Defining clear goals and objectives for the program is critical. Juvenile mussels can be produced for basic life history research, toxicity testing, restoration of historical populations and the ecosystem services they provide, and recovery of imperiled species. A planning team that includes local experts and other stakeholders can help identify the primary goals and objectives. Working with stakeholders early in the process also can help ensure agreement on a path forward and commitment to implementing the planning team's recommended actions.

If restoration and recovery are identified as one of the program goals, the planning team must first determine if propagation is the best restoration strategy for any given mussel species or population. Controlled propagation is not a substitute for addressing factors responsible for an endangered or threatened species' decline (USFWS and NMFS, 2000), and should be considered as a last resort. If the factors responsible for the decline are not addressed, propagation efforts are likely to fail. The United States Policy Regarding Controlled Propagation of Species Listed under the Endangered Species Act states that the first priority is to recover wild populations in their natural habitat. Before collecting a single gravid mussel or building a single juvenile culture system, consider any and all feasible alternatives to propagation, such as habitat restoration and water quality improvements. Suitable habitat that provides the necessary resources for growth and reproductive success is critical. Stocking mussels in degraded habitats will not help recover the species and ultimately will be a waste of money. Investing in long-term solutions like habitat restoration, while simultaneously working to improve propagation technology might be a better strategy. Once the habitat is restored, a stocking program can help meet restoration objectives for the species.

Unfortunately, many freshwater mussel populations have declined to the point that the time for last resorts has arrived. In some cases, populations are so low that extinction is imminent. The purple catspaw (*Epioblasma obliquata obliquata*) provides an excellent example (Figure 1.3). Once widespread in the southern Ohio River basin, the purple catspaw is now considered one of the rarest mussel species in North America. Initially thought to be functionally extinct, a breeding population was discovered in Killbuck Creek, Ohio, in 1994. Since the discovery of this new population, Killbuck Creek has become degraded to the point that drastic measures are now necessary to prevent extinction of the purple catspaw. Efforts to address the factors responsible for the decline of catspaw are currently underway, including fencing out livestock to restore stream banks, prevent sedimentation and restore the stream channel. Unfortunately, this species could go extinct before the benefits of habitat restoration are fully realized. Thus, propagation will play a critical role in preventing extinction of this species.

Taking no conservation action also needs to be carefully considered. If any proposed conservation measure, including propagation, has the potential to do more harm to imperiled species than good, it may be better to do nothing. If all feasible alternatives have been exhausted and it becomes clear that propagation is needed to recover a species or prevent extinction, the remaining questions should be addressed before propagation begins. All of these questions are