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Southern Appalachian Freshwater Mussels (Unionida): Threats and a Call to Action

Abstract:

Freshwater mussels (Unionida) are integral to the health of southern Appalachian freshwater ecosystems. Functioning as indicator and keystone species in their native ranges, freshwater mussels provide a variety of ecosystem services in the form of sediment mixing, nutrient deposition and conversion, and nursery habitat. Due to their life history involving a parasitic glochidial stage in which larval mussels parasitize fishes, freshwater mussels are inherently dependent upon the presence of native fish species in their environment for dispersal and recruitment. In turn, high levels of local extinction and extirpation have propelled Unionid mussels to the frontlines of extinction worldwide. I propose to protect this order of mollusks through the increase of water management regulations for coal mining and urban development. Additionally, I advocate for the use of nongame fish hatcheries in the reintroduction of native fish species that may serve as hosts for mussel glochidia. Finally, I state the importance of local interaction in the process of conserving this group of mollusks. As aquatic ecosystems continue to be threatened by a variety of human activities, it is increasingly important to protect species which play a disproportionate role in ecosystem health and function such as freshwater mussels.

Introduction

Southern Appalachia is an extremely biodiverse area located in the mountainous southern United States. Considered a biodiversity hotspot, this region is home to a variety of aquatic species, including many endemic fishes, crayfishes, aquatic insects, and mollusks (Crandall & Buhay et al. 2007, Milanovich et al. 2010, Lopes-Lima et al. 2018). Over 290 freshwater fish species exist within Tennessee alone, more than can be found in all of Europe (Stein et al. 2000). Freshwater mussels (Order: Unionida) are an integral part of these communities, playing key roles in ecological processes such as sedimentation, water filtration, and food-web dynamics (Spooner & Vaughn 2006, Vaughn 2017). However, the unique life history of Unionid mussels, which includes a parasitic life stage early in their development, has put this group of mollusks at extreme risk of extinction due to the threats posed against their host-affiliate fish species. Freshwater bivalves are considered one of the most threatened clades of animals on earth, with over 40% of species near threatened, threatened, or extinct. The order Unionida makes up the majority of these threatened bivalves and, while found globally, are most prevalent within southern Appalachia, making this region a necessary focus for research and conservation (Lopes-Lima et al. 2018). It is therefore imperative that a comprehensive conservation plan to protect these mussels and their host fish species be put in place, as mussels greatly depend on native fish for recruitment due to their parasitic larval life stage (Geist et al. 2006). I propose this be done through land and water protection, the supplementation of native fish species through hatchery programs, and scientific outreach to southern Appalachian communities.

Why protect freshwater mussels?

While many endemic species within southern Appalachia are threatened by anthropogenic change, few play as big a role in ecosystem function as freshwater mussels. Unionids provide a suite of services for aquatic ecosystems. Some species, as in the case of the eastern pearlshell mussel (*Margaritifera margaritifera*) native to the eastern US, are considered keystone and indicator species due to their major influence on aquatic ecosystems and indicative presence in healthy bodies of water (Geist 2010). Freshwater mussels serve as dominant filter feeders in many aquatic ecosystems (Strayer et al. 1999). By mixing sediment through burrowing, depositing nutrients as feces and pseudofeces, and stabilizing stream benthos at high densities, Unionids can have direct and indirect effects on nutrient cycling within a given ecosystem (Strayer 2014, Vaughn & Hakenkamp 2001). Dame (1996) found that at high densities, such as those seen in healthy mussel bed communities, freshwater mussels can regulate phytoplankton abundance and water clarity through their feeding activity. Mussel beds also serve as refuge for a wide variety of associated organisms, including juvenile fish, aquatic insects, and epiphytic algae (Geist 2010, Vaughn & Hakenkamp 2001). In short, freshwater mussels are integral to the health of many aquatic ecosystems, and are useful tools in the evaluation of stream health and the conservation of other species, making it necessary to protect them.

Threats to Unionida

Unionids are long-lived, sedentary organisms with complex life cycles, making them highly vulnerable to anthropogenic change (Strayer et al. 2004, Galbraith et al. 2018). Coupled with high sensitivity to changes in water quality, freshwater mussel populations have severely declined with modifications to southern Appalachian water systems over the past century (Strayer & Malcom 2012). Much of this decline can be attributed to dam development in the latter half of the 20th century on many river systems throughout the southern United States (Haag 2019). Dams completely alter hydrological features such as sedimentation, temperature, dissolved oxygen, and water velocity (Downward & Skinner 2005). By increasing levels of sedimentation upstream, and allowing little to travel downstream, dams remove important nutrients from the water column that Unionids depend on. In contrast, populations that exist upstream of dams experience much higher levels of sedimentation, which can impact the efficacy of mussel filter feeding (Kryger & Risgard 1988). Decreased velocity above dams only compounds this effect (Vaughn & Hakenkamp 2001). Even more detrimental to the long-term stability of mussel populations is the habitat fragmentation that occurs when a dam is built. This can result in decreases in gene flow throughout a given river system, effectively decreasing genetic diversity within mussel populations and making them more vulnerable to environmental stochasticity (Liu et al. 2020). Additionally, mussel species that depend on migratory fish such as catadromous eels (*Anguilla rostrata*) may lose access to their host species when dams act as barriers (Galbraith et al. 2018). However, while dam building has relatively subsided in recent decades within the southern Appalachian Basin, mussel populations have continued to plummet, implying other anthropogenic factors are at play.

Water pollution in the form of chemical runoff continues to threaten freshwater mussel populations. Surface coal mining, the process by which mountaintops are removed to expose buried seams of coal for exploitation, is a prevalent, century old practice throughout Southern Appalachia (Evans et al. 2015). Chemical waste produced in these mining operations has serious implications for aquatic biodiversity as a whole. Studies surrounding the effect of coal mine runoff into proximal streams have found that across all invertebrate taxa measured affected streams had one third less species richness, and nearly half the abundance, of those that were unmined (Giam et al. 2018).

Land-use practices are an overlooked but ubiquitous factor in the decline of Unionid mussels. The introduction of fine sediments into river systems due to erosion and sediment runoff has been shown to drastically change the species composition of mussel beds (Box & Mossa 1999). After alteration of a gravel bed in Olentagny River of Columbus, Ohio through channelization and highway construction, 14 species of Unionid mussels disappeared within three years. This was attributed to the complete alteration of the sediment regime in the river bed from gravel and cobble to fine silt (Stein 1972, Box & Mossa 1999). There are many mechanisms by which the introduction of fine sediment can interfere with mussel behavior and survival (Box & Mossa 1999). Fine silt and clay can clog the gills of mussels and interfere with their filter feeding (Ellis et al. 1936). It can also inhibit burrowing by creating a packed surface of sediment. Finally, silt can fill interstitial spaces in sediment, which juvenile mussels depend on for feeding (Gordon et al. 1992). But while there are a variety of anthropogenic stressors that impact the recruitment and survival of freshwater mussels, their parasitic larval stage is likely what makes this group of mollusks most vulnerable (Modesto et al. 2017).

While Unionid mussels are sensitive to anthropogenic shifts in the environment due to their physiology and feeding behavior, evidence suggests that their life history puts them at the greatest risk of extinction. Similar to other groups of mollusks, freshwater mussels undergo metamorphoses as they develop from larvae into adults. However, Unionid mussels begin life as Glochidia, obligate parasites of a variety of fish and amphibian species. During a spawning event, a single adult mussel can release thousands of glochidia (several million a year), each with the goal of attaching to a fish host, or in rare cases an amphibian (Geist 2010, Cmiel et al. 2018). The larval mussels clamp down on specific tissues of their host, often their gills or fins, where they will be encysted by the host's epithelial cells. The glochidia will then feed on the blood of the host for up to several months, eventually developing into a free-living mussel that drops off and settles into the sediment (Bauer & Vogel 1987, *Figure 1*). Due to this unique life stage, Unionid mussels are highly dependent on viable host fish populations. Jansen and Hansen (1991) found more than 99.99% of glochidia fail to attach to a host, resulting in their death a few days after they are released. In turn, fecundity is unlikely to be the limiting factor in mussel recruitment, but rather the density of viable hosts. In addition, mussel glochidia are often host specific, parasitizing only a handful of endemic fish species (Geist 2010). This creates serious challenges for mussel populations where native fish density is low, as the likelihood of successful transmission of their larvae decreases with host density (Geist et al. 2006, Galbraith et al. 2018). To effectively protect this unique group of mollusks, focus must be placed on the rejuvenation of native fish populations that are in decline, as these fish play a vital role in mussel recruitment.

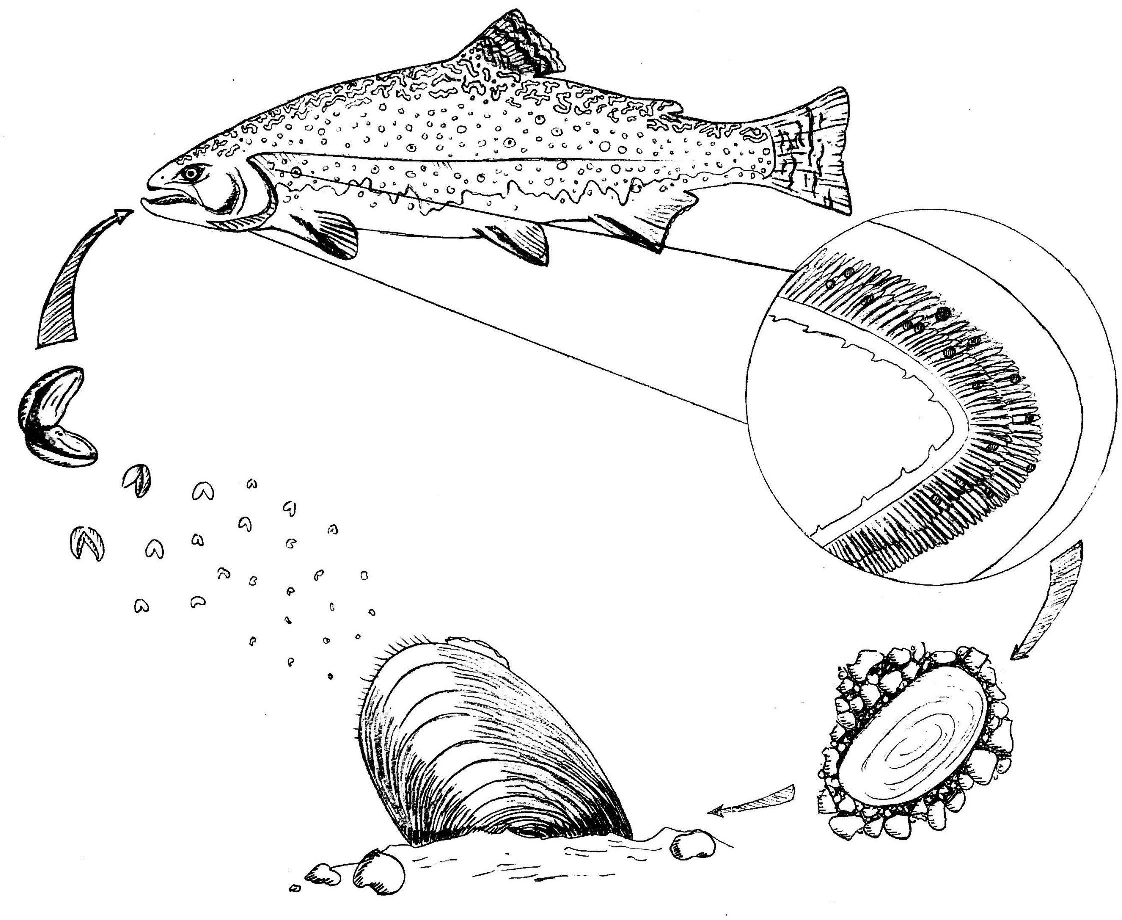

*Figure 1: The life cycle of a freshwater mussel: the eastern pearl mussel (*Margaritifera margaritifera*) and its affiliate-host the brook trout (*Salvelinus fontinalis*), illustrated by Cormac Toler-Scott.*

A comprehensive conservation plan

To successfully protect the remaining freshwater mussel species of southern Appalachia, I propose a multifaceted management plan, which will be carried out by an appointed recovery team. Leadership has emerged as the champion of successful recovery of endangered species (Manolis et al. 2009). A recovery team that's sole purpose is the rehabilitation of mussel populations in the southern US will ensure cohesive, timely, and responsible decision making, attributes of conservation management that greatly contribute to success (Martin et al. 2012). However, it is unrealistic to expect a single entity to monitor and protect hundreds of species over a vast area, each with separate populations that require localized management. It is imperative that this recovery team communicate with already established agencies working to protect mussel populations in a given area, and unite these efforts nationally to promote communication and effective policy enaction. This recovery team will have three major goals including: increased legislation to improve the protection and management of land and water, the supplementation of host-affiliate fish species, and the education of local communities on the role of mussels in the aquatic ecosystems of southern Appalachia.

The protection and management of land and water is considered one of the most effective conservation measures in the recovery of a species. River basin degradation is often the product of poor water management, which comes in many forms. Water pollution in the form of manufacturing waste, untreated sewage, and agricultural runoff is a common contributor to decline in river health (Palaniappan et al. 2010). Grey infrastructure in the form of dams and channels is also a culprit of serious declines in aquatic biodiversity (Vörösmarty et al. 2010). All of these factors impact the health of mussel populations, but due to their longevity and immense reproductive capacity even at an old age, the potential for freshwater mussel recovery is high if these stressors can be eliminated (Bauer 1992). Increased legislation to protect land and water is necessary if any efforts to rehabilitate mussel populations are to be effective. Short-term solutions should come in the form of increased regulations on surface coal mining for waste disposal and mining permits. This would decrease levels of introduced heavy metals in to headwaters, which greatly impact stream health as a whole. Additionally, the transition from hydroelectric power to a more renewable source of energy and the subsequent removal of dams along these river systems would be a long-term solution for Unionid population connectivity, benefiting freshwater mussels immensely (Liu et al. 2020). But while it is easy to state these facts, employing them is much more of a challenge, as the vast majority of the United States' electricity is derived from coal and hydroelectricity (IEA 2019). In turn, other solutions such as the supplementation of native fish species, must be adopted while this regime shift takes place.

An important step in the conservation of freshwater mussels is the protection of native fish species that contribute to their life history. As global extinction rates continue to rise, extinctions are expected to be highest for parasite and mutualist species, where extirpation of one symbiote incites that of the other (Spooner et al. 2011). Many of the anthropogenic stressors that affect Unionid populations are conjointly influential on their native host species, which can compound negative effects by decreasing mussel recruitment (Geist et al. 2006). Between 1898 and 2006, 57 species of freshwater fish went extinct in North America, and it is estimated that this will increase to 86 species by 2050 (Burkhead 2012). Due to southern Appalachia's high diversity of endemic fish species, there is increasing concern that this is where many of those extinctions will take place. Only a handful of studies have investigated freshwater mussel response to host fish limitation, but evidence is conclusive that the loss of these relationships can be detrimental for a given mussel population (Geist et al. 2006, Fritts et al. 2012). Indeed, the reintroduction and rehabilitation of native fish species has been shown to positively affect mussel recruitment. Galbraith et al. (2018) found that with the reintroduction of migratory American eels (*Anguilla rostrata*) to a portion of the Susquehanna River where dams had restricted access significantly increased mussel recruitment of the eastern elliptio mussel (*Elliptio complanata*). By supplementing native fish populations through hatchery rearing, it may be possible to stave off impending mussel extinctions (Galbraith et al. 2018). Of course, this must be done in tandem with the protection of these waterways, as present conditions are in many cases what led to these extirpations originally. Hatcheries such as Conservation Fisheries Inc. (Conservation Fisheries INC) have set out with the goal to preserve aquatic biodiversity in the rivers of Tennessee, where fish biodiversity is extremely high. Their facility propagates more than 65 imperiled native fish species, with the hopes of restoring these populations to their former numbers. The reintroduction of these fishes not only promotes fish biodiversity, which is an important feature of aquatic ecosystem health and stability, but may increase mussel recruitment conjointly, as many of these fish likely serve as hosts for Unionid glochidia. Additionally, evidence suggests the relationship between mussels and their host may be a form of mutualism, as mussel beds provide nursey for juveniles of host species (Ziuganov et al. 1994). In turn, I propose partnering with nongame fish hatcheries and expanding their facilities, as both fishes and mussels can benefit from the reestablishment of native fish populations. Still, for conservation measures such as this to succeed, local communities must be willing to take part in the protection of freshwater mussel populations.

Scientific outreach is often thought of in a unidirectional manner, whereby scientists are informing the general public, educating communities on how their behavior impacts their surroundings, and therefore assuming communities do not have knowledge to contribute to possible solutions. This perspective is a product of ignorance, and can have long lasting negative effects on the trust these communities have in conservation motives (Shebitz & Oviedo 2018). It is therefore important when building relationships with locals in areas of interest to develop a two-way exchange of knowledge, and build respect, rather than disdain, for the protection of biodiversity (Shebitz & Oviedo 2018, Mckinley et al. 2015). An integral aspect to the successful recovery of freshwater mussels in the southern US is the elucidation of the important roles that mussels play in aquatic ecosystems to the general public. By informing the public about the presence of these unique mussel communities in their rivers and streams, locals can become advocates for these endangered species (Mckinley et al. 2015). As a part of my proposal, significant focus will be placed on involving the general public, through schools and citizen science programs, in the rehabilitation and conservation of mussel habitat. Allowing active participation in the restoration of waterways is an effective way to teach the community about the role mussels play in ecosystem function, and can give individuals a sense of pride in their land and the remarkable organisms they share it with.

Concluding remarks

As the need for energy and urban development continues to increase in response to human proliferation and migration, protecting inland aquatic ecosystems from catastrophe will become increasingly challenging. While supplementation of native fish species may stall the impact of anthropogenic stressors on freshwater mussels, it is by no means the only thing that must be done if these mussels are to return to their former numbers. Hatcheries are not a new development in the rejuvenation of fish populations, and hold challenges of their own, both from economic and ecological standpoints (Milot et al. 2013). Lastly, while there is a general understanding of freshwater mussel life history, much more research must be performed if we are to link individual species to specific hosts. This is necessary if hatchery reintroductions and supplementations are to benefit mussel species directly. Freshwater ecosystems are dynamic and complex systems that hold a great deal of value both in their biodiversity and their inherent influence on the quality of inland water resources (Jackson et al. 2001). To truly protect the freshwater mussels of southern Appalachia, a regime shift must take place, where the preservation of natural systems and biodiversity as a whole becomes of equal or greater value to national economic gain.

Bibliography:

Bauer G. 1992. Variation in the Life Span and Size of the Freshwater Pearl Mussel. *Journal of Animal Ecology* 61(2): 425-436.

Bauer G & C Vogel. 1987. The parasitic stage of the freshwater pearl mussel (*Margaritifera margaritifera*) I. Host response to glochidiosis. *Archiv für Hydrobiologie* 76: 393–402.

Box J & J Mossa. 1999. Sediment, Land Use, and Freshwater Mussels: Prospects and Problems. *Journal of the North American Benthological Society* 18(1): 99-117.

Burkhead NM. 2012. Extinction Rates in North American Freshwater Fishes 1900–2010. *BioScience* 62(9): 798–808.

Ćmiel AM, K Zając, AM Lipińska, & T Zając. 2018. Glochidial infestation of fish by the endangered thick-shelled river mussel *Unio crassus*. *Aquatic Conserv: Mar Freshw Ecosyst* 28: 535– 544.

Conservation Fisheries. (n.d.). Retrieved from https://www.conservationfisheries.org/

Crandall KA & JE Buhay. 2007. Global diversity of crayfish (Astacidae, Cambaridae, and Parastacidae—Decapoda) in freshwater. In: Balian EV, C Lévêque, H Segers, K Martens. (eds) Freshwater Animal Diversity Assessment. *Developments in Hydrobiology* 198.

Dame RF. 1996. Ecology of Marine Bivalves: An Ecosystem Approach. CRC Press, New York.

Downward S, & K Skinner. 2005. Working Rivers: The geomorphological legacy of English freshwater mills. *Royal Geographical Society* 37: 138– 147.

Ellis MM. 1936. Erosion silt as a factor in aquatic environments. *Ecology* 17:29-42

Evans DM, CE Zipper, ET Hester, & SH Schoenholtz. 2015. Hydrologic Effects of Surface Coal Mining in Appalachia (U.S.). *Journal of the American Water Resources Association* 51(5): 1436- 1452.

Fritts AK, MW Fritts, DL Peterson, DA Fox, & RB Bringolf. 2012. Critical linkage of imperiled species: Gulf Sturgeon as host for Purple Bankclimber mussels. *Freshwater Science* 31:1223–1232.

Galbraith HS, JL Devers, CJ Blakeslee, JC Cole, B St. John White, S Minkkinen, & WA Lellis. 2018. Reestablishing a Host-Affiliate Relationship: Migratory Fish Reintroduction Increases Native Mussel Recruitment. *Bull Ecol Soc Am* 99(4): 1841-1852.

Geist J. 2010. Strategies for the conservation of endangered freshwater pearl mussels (*Margaritifera margaritifera* L.): a synthesis of Conservation Genetics and Ecology. *Hydrobiologia* 644: 69–88.

Geist J, M Porkka & R Kuehn. 2006. The status of host fish populations and fish species richness in European freshwater pearl mussel (*Margaritifera margaritifera*) streams. *Aquatic Conservation: Marine and Freshwater Ecosystems* 16: 251–266.

Giam X, JD Olden & D Simberloff. 2018. Impact of coal mining on stream biodiversity in the US and its regulatory implications. *Nat Sustain* 1:176–183.

Gordon ND, TA McMahon, & BL Finlayson. 1992. Stream Hydrology: an introduction for ecologists. New York, NY, USA: John Wiley and Sons.

Haag WR. 2019. Reassessing Enigmatic Mussel Declines in the United States. *Freshwater Mollusk Biology and Conservation* 22(2): 43-60.

IEA. 2019. Coal 2019. Paris https://www.iea.org/reports/coal-2019

Jackson RB, SR Carpenter, CN Dahm, DM McKnight, RJ Naiman, SL Postel, and SW Runnin. 2001. Water in a hanging world. *Ecological Applications* 11: 1027-1045.

Jansen WA & Hanson MJ. 1991. Estimates of the number of glochidia produced by clams (*Anodonta grandis simpsoniana* Lea), attaching to yellow perch (*Perca flavescens*), and surviving to various ages in Narrow Lake, Alberta. *Canadian Journal of Zoology* 69(4): 973-977.

Kryger J & HU Risgard. 1988. Filtration-rate capacities in 6 species of European fresh-water bivalves. *Oecologia* 77:34–38.

Liu X, R Wu, X Chen, et al. 2020. Effects of dams and their environmental impacts on the genetic diversity and connectivity of freshwater mussel populations in Poyang Lake Basin, China. *Freshwater Biology* 65: 264– 277.

Lopes-Lima M, LE Burlakova, AY Karatayev, *et al.* 2018. Conservation of freshwater bivalves at the global scale: diversity, threats and research needs. *Hydrobiologia* 810: 1–14.

Manolis JC, KM Chan, ME Finkelstein, S Stephens, CR Nelson, JB Grant, & MP Dombeck. 2009. Leadership: A New Frontier in Conservation Science. *Conservation Biology* 23: 879-886.

Martin T, S Nally, A Burbidge, S Arnall, S Garnett, M Hayward, L Lumsden, P Menkhorst, E McDonald-Madden, & H Possingham. 2012. Acting fast helps avoid extinction. *Conservation Letters* 5:274-280.

McKinley D, A Miller-Rushing, H Ballard, R Bonney, H Brown, D Evans, R French, J Parrish, T Phillips, S Ryan, L Shanley, J Shirk, K Stepenuck, J Weltzin, A Wiggins, O Boyle, R Briggs, SF

Chapin III, D Hewitt, & M Soukup. 2015. Investing in Citizen Science Can Improve Natural Resource Management and Environmental Protection. *Issues in Ecology* 19:1-27.

Milanovich JR, WE Peterman, NP Nibbelink, & JC Maerz. 2010. Projected Loss of a Salamander Diversity Hotspot as a Consequence of Projected Global Climate Change. *PLOS ONE* 5(8): e12189.

Milot E, C Perrier, L Papillon, JJ Dodson, & L Bernatchez. 2013. Reduced fitness of Atlantic salmon released in the wild after one generation of captive breeding. *Evolutionary applications 6*(3): 472–485.

Modesto V, M Ilarri, AT Souza, M Lopes-Lima, K Douda, M Clavero, R Sousa. 2017. Fish and mussels: Importance of fish for freshwater mussel conservation. *Fish and Fisheries* 19(2): 244-259.

Palaniappan M, PH Gleick, L Allen, MJ Cohen, J Christian-Smith, & C Smith. 2010. Clearing the Waters: A Focus on Water Quality Solutions. Nairobi. UNEP.

Shebitz D & A Oviedo. 2018. Learning from the Past: Reflecting on the Maya-ICBG Controversy in the Classroom. *Ethnobiology Letters* 9: 59-66.

Spooner DE & CC Vaughn. 2006. Context-dependent effects of freshwater mussels on the benthic community. *Freshwater Biology* 51:1016–1024.

Spooner DE, MA Xenopoulos, C Schneider, & DA Woolnough. 2011. Coextirpation of host–affiliate relationships in rivers: the role of climate change, water withdrawal, and host-specificity. *Global Change Biology* 17: 1720-1732.

Stein CB. 1972. Population changes in the naiad mollusk fauna of the lower Olentangy River following channelization and highway construction. *Bulletin of the American Malacological Union for* 1972:47-49.

Stein BA, L Kutner, & J Adams. 2000. Precious Heritage. Oxford, UK: Oxford University Press.

Strayer DL. 2014. Understanding how nutrient cycles and freshwater mussels (Unionoida) affect one another. *Hydrobiologia* 735: 277-292.

Strayer DL & HM Malcom. 2012. Causes of recruitment failure in freshwater mussel populations in southeastern New York. *Ecological Applications* 22:1780–1790.

Strayer DL, NF Caraco, JF Cole, S Findlay, & ML Pace. 1999. Transformation of freshwater ecosystems by bivalves. *Bioscience* 49: 19-27.

Strayer DL, JA Downing, WR Haag, TL King, JB Layzer, TJ Newton, JS Nichols. 2004. Changing Perspectives on Pearly Mussels, North America's Most Imperiled Animals. *BioScience* 54(5): 429–439.

Vaughn CC. 2017. Ecosystem services provided by freshwater mussels. *Hydrobiologia*. 810(1):1-13.

Vörösmarty C, P McIntyre, M Gessner, *et al.* 2010. Global threats to human water security and river biodiversity. *Nature* 467**:** 555–561.

Ziuganov V, A Zotin, L Nezlin, V Tretiakov. 1994. The freshwater pearl mussels and their relationships with salmonid fish. VNIRO, Russian Federal Institute of Fisheries and Oceanography, Moscow. Page 104.