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The Freshwater Mollusk *Dreissena polymorpha* (Zebra Mussel) - A Review: Living, Prospects and Jeopardies

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Authors' contributions

This work was carried out in collaboration between both authors. Author KD read and approved the final manuscript.

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Review Article

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ABSTRACT

This review paper aims to address the topic of the living, prospects as well as jeopardies of the invasive Zebra Mussel. Broad literature reviews have been taken place to gather as many facts on this species as possible to summon all the most significant information up in one paper to be available for everyone. To get a better understanding of freshwater mussels in general, a short review of freshwater mussel diversity in America has been written also. The review paper focuses especially on living, prospects, and jeopardies in North America. The review revealed, freshwater mussels to be of practical importance and of great primeness for scientific research due to their unique life cycle. Especially the freshwater mollusk *Dreissena polymorpha* (Dreissenidae), colloquial known as the zebra mussel draws interest due to the mollusks' invasive character and their tremendous filtering capacity. Once originated from the Ponto-Caspian region and currently present in 33 European Countries and 33 states of North America the freshwater bivalve draws interest all over the world. Their larval stage allows broad invasions of aquatic systems. Even though they can both harm their habitat as well as other organisms living in it, *Dreissena*

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polymorpha enormous filtering capacity can be utilized effectively if managed right. However, a lack of natural enemies and environmentally friendly pesticides makes control of *Dreissena polymorpha* in open water impossible.

Keywords: Dreissena polymorpha; ecological impact; freshwater mussel; mussel control; water treatment; zebra mussel.

1. INTRODUCTION

With a worldwide imperiled status and thus practical importance, freshwater mussels are of great importance. They generated interest due to their unique life cycles, aggregate distribution and ancient origin. Colloquial known as freshwater mussels, the bivalve order Unionoida, pearly mussels or naiades, exist in rivers and lakes of all continents except Antarctica [1,2,3].

Nonetheless, some mussel species draw more research interest than others, especially members of the family Unionidae and Dreissenidae. The invasive, biofouling freshwater bivalve Zebra Mussel (*Dreissena polymopha)* draws a great interest in different aspects of biological research.

Currently present in 33 European countries and in 33 states of North America and two Provinces of Canada, the small mussel gains obligatory interest all over the world [4,5].

With their byssal threads they attach to hard surfaces and substrate, forming extraordinarily large colonies [5].

Mussels and explicitly zebra mussels are underestimated but one of the most promising organisms for technical application and research purposes in many areas. In general, mussels can serve as an eco-friendly method of pollutant assessment such as the detection of metallic element pollution (ME) [6]. Pollution is a major global concern, because the inorganic contaminants are continuously released into the environment by human activity [6]. ME removal is possible with microorganisms living on aquatic macrophyte tissue. Therefore, mussels are suitable for wastewater treatment. Especially *Dreissena polymorpha*, know as the Zebra mussel, has extraordinary abilities for wastewater treatment. An enormous filtering capacity, ranging from 5 to 400 mL/bivalve/h, along with high population density of more than 700000 individuals/m^2 [7] and the ability to produce feces and pseudofeaces, leading to higher rates of absorbed contaminants, are only few of a great variety of advantages [8]. The zebra mussel is a notorious freshwater biofouling pest, and highly resistant to natural and anthropogenic stresses and to bioaccumulate lipophilic contaminants [9]. Their filtration capabilities of up to 90% of organic matter from water make them capable of altering aquatic environments. Decreasing phytoplankton biomass and shifts in phytoplankton community composition are effects of overpopulation [10], which is actually an ability known from submerged macrophytes (*Eleodea nuttallii*), posing shelter to grazers like *Daphnia* [11] but also by their relatives the quagga mussels (*Dreissena rostriformis bugensis*) [12]. However, *Dreissena polymorpha* poses harm sometimes even to bigger organisms living in biota like bigger freshwater mussels from the order of Unionida, thus putting a tremendous number of freshwater mussels at risk of extinction [13]. Hardly any predator can diminish zebra mussel colonization sustainably, making them dangerous for eco-systems [14], and control of *Dreissena polymorpha* is extraordinary constrained [15] thus also leading to major economic impacts [3].

This review papers intent is to give an overview of freshwater mussel diversity and habitat in North America, but further addresses the major topic of the possibilities and revenues of *Dreissena polymorpha* alias Zebra Mussels. Addressing the topic of the invasive species *Dreissena polymorpha* is significant, since invasions of non-native species are one of the leading mechanisms of global environmental change, especially in freshwater ecosystems.

2. FRESHWATER MUSSEL DIVERSITY IN NORTH AMERICA

Mussels, or bivalves more precisely, are mollusks without a head and with a single foot enclosing the visceral mass. They also have two pair of gills and sexes are typically separate. The body is composed of calcium carbonate, either as calcit or aragonitic crystal and each mollusk has two valves surrounding the body. Mollusks of the unioniforme family have aragonitic crystal structures on shells. The bivalve order *Unionoida*, also known *pearly mussels* or *naiades*, exist in rivers and lakes on all continents except Antarctica [2,3]. The size of Dreissena poylmorpha for instance, can reach a maximum length of about 5.0 cm (2 inches). However, as with all-natural organisms, their sizes can differ.

Freshwater bivalves are not a monophyletic group. Solely the term freshwater bivalve is not utterly predicative. More than 19 families of bivalves have at least one representative in freshwater, resulting in suggested 14 different invasions of freshwater. Small to large radiations in freshwater are given by a least nine families: Corbiculidae, Sphaeriidae, Dreissenidae, and the unioniforme families: Hyriidae, Margaritiferidae, Unionidae, Etheriidae, Iridinidae, and Mycetopodidae. However, most families contain only few genera or species.

Florida's pioneer naturalist Charles Torrey Simpson (1846-1932) consolidated the previous century's more than 4,000 named species to approximately 1,300 species and subspecies in fewer than 80 genera. With Simpsons Magnum Opus, a solid framework for family-level classification was given. However, his work was revised numerous times [3]. Considering the diversity of freshwater mussels, the global diversity is currently estimated to 927 species in 179 genera [14].

The lifespan and life history of freshwater bivalves differs. Species from primarily marine bivalve families have veliger or brooded larvae. Unioniforme bivalves are special for that matter, since they have a compulsory parasitic larval stage in the gills fines or sides of a host fish [16]. The Mississippi River basin contains the largest number of endemic freshwater mussels in the world [13].

Shell shape varies among the families as well [17] It depends partially on their phylogenetic history and on the unique habitat. For example, the shells of bivalves living buried in cobble and gravel substrate are much thicker than those of byssally attached mussels. Unioniforme families are mostly infaunal organism living buried in substrate, varying from sand to cobbels and gravel. However, some species like the blue mussel or the zebra mussel attach to hard surfaces with their byssal threads [17].

Furthermore, North America is holding the highest diversity within the order of Unionoida, the bivalve showing the highest diversity within a family. More precisely, North America is home to approximately 300 taxa (species and subspecies) within the families Unionidae and Margaritiferidae [3].

Data on freshwater biodiversity is poor [14]. Further, North America, harboring the most diverse freshwater mussel fauna on earth, has high endemism at the continental scale and within individual river systems. Several attempts have been made to classify North American mussel diversity into biogeographical faunal regions over the past 100 years. A study by Wendell R. Haag, capturing the diversity of freshwater mussels in North America has revealed, that the Mississippian Region dominates the North American Fauna [18]. For that previous fauna classifications were not based on objectivity and primarily based on the presence of endemic species and intuitive assessments of faunal differences examining the river systems, Haag classified the four regions "Mississippian Region", Eastern Gulf Region", "Atlantic Region" and "Pacific Region" in his 2010 study considering the region from the Rio Grande system northwards [18].

Mississippian provinces are considered to hold widely distributed species, still some province show endemism. In contrast to the most distinct fauna in North America, the Pacific Region, which shows a similarity to the Eurasian mussel fauna, the Atlantic and Eastern Gulf regions have characteristic endemic faunas, too. This shows limited past connectivity with the Mississippian Region. Nonetheless, the affinity of the Pacific Region to the Eurasian Fauna is remarkable and was already noted by Charles Torrey Simpson, who also gave this region the name "Palearctic Region" [18].

Freshwater biodiversity is decreasing at a higher rate than in terrestrial or marine ecosystems in regards to freshwater mussel diversity. It is thought that 35 of the 297 native North American freshwater mussels have gone extinct and three quarters are imperiled [19].

3. IDENTITY OF *Dreissena polymorpha*

The mollusk *Dreissena polymorpha* gets its name from the distinctive dark strips on their pale shell. Albeit, especially older individuals won't necessarily show such coloration [5]. Populations of the species can alter aquatic environments through their substantial filtration capabilities and are considered as invasive alien species in the whole United States and all parts of Europe. The bivalves have a life span of about three years. However, there are also reports about *Dreissena polymorpha* living up to an age of 19 years. The longevity of *Dreissena.polymorpha* generally various from 2-19 years, depending on the habitat, living conditions and exposure to threats and toxins [8,20,21] and grows from 0.5 cm to 1.0-5.0 cm, (Fig. 1).

Adults are sexually mature at 8–9 mm in shell length (*i.e.* within one year in favorable growing conditions) [23].

The Zebra Mussel is similar in appearance to the quagga mussel (*Dreissena bugensis*), however differences in shell morphology make a distinction possible*. Dreissena polymorpha* has a flat underside, whereas *Dreissena.bugensis* does not, means the quagga mussel will fall over when placed on a flat surface, zebra mussels do not. Additional distinctions can be assessed with genetic identification [24,25].

Zebra Mussels have a distinct life-circle. Unlike every Native freshwater Mollusk in North America, the bivalves attach to solid surfaces using adhesive byssal fibers and possess a planktonic larval (veliger) stage. The larva can remain in the water column for several weeks before settlement. [13]. There are high levels of mortality during their free-living stage and metamorphosis. When seized by the current and carried downstream in rivers or estuaries, they may perish.

Rapid spread of the mussel has been facilitated by their high fecundity of up to one million eggs per female, their ability to attach on surfaces using their byssal threads and their veliger larval stage of some weeks, making downstream transport utterly simple and fast [5].

Without the account of natural freshwater mussel density, boundary layer effects, flow rates or elevated algal concentration, many of the zebra mussels' large-scale effects rely on static laboratory experiments, through which extrapolations for the filtration rates were assessed. Still, their ability of affecting aquatic environments profoundly remains. Zebra Mussels are filter feeders, thus can remove over 90% of organic matter form the water.

Submerged macrophytes (*Elodea nuttallii*) have great effects on phytoplankton biomass in shallow lake ecosystems [26,27].

They pose refuge to Daphnia (*Daphiindae*), a phytoplankton grazer, thus stabilize clear water state [11].

Especially *Simocephalus vetulus* and *Ceriodaphnia* are held responsible for lower phytoplankton biomass in the presence of real and artificial macrophytes [28].

Fig. 1. Zebra Mussels *(Dreissena polymorpha)* [22]

However, Zebra Mussels can be major consumers of phytoplankton, too, making them significant top-down controllers for phytoplankton levels. But besides changing phytoplankton biomass levels, *Dreissena polymorpha* is also capable of causing shifts in phytoplankton community composition, thus makes them affecting phytoplankton taxa. Considering their enormous filtering capacity, clear water state might be stabilized by *Dreissena polymorpha* too, however, thus the mussel is also a jeopardy to organisms feeding on and dependent of phytoplankton biomass.

It should be also taken into consideration that cyanobacterial blooms appearing shortly after zebra mussels have been established to an aquatic system, posing serious danger to humans. Cyano-bacteria are known to produce hepatotoxins which present a serious health risk for human populations [10].

3.1 Larval Stage

When water temperature reaches 12 °C (17-18°C in some cases) Zebra Mussels begin to spawn [29]. Females usually reproduce in their second year.

In one reproductive cycle, over 40,000 eggs can be laid and up to one million in a season.

The fertilized eggs, called veligers, emerge after 3 to 5 days and are then free-swimming for about a month and most effectively develop in temperatures ranging 20-22°C. Dispersal of veligers is controlled by outer circumstances, such as current and wind-strength [30,31], affecting both spatial patterns of pelagic veliger density and benthic adult dispersion.

A postveliger is a veliger that undergoes morphological changes, such as development of the siphon, foot, organ systems and blood. In general, larval stage can be segmented into the following stages: veliger (preshell, straight-hinged, umbonal), postveliger (pediveliger, plantigrade), and juvenile (settling stage) [32].

In the last stage, the juvenile mollusk begins to settle the bottom and crawl about on it by means of a foot to search for suitable substrate. The juvenile larvae then attach to some substrate, thus leading to a high larvae mortality rate of 99%, due to settlement onto unsuitable substrates. Also, changes in temperature and oxygen affect the utterly sensitive mollusk greatest at this stage [23].

4. SPREAD

Originated from the Ponto-Caspian region (area of the black sea and Caspian Sea, Azov Seas), striped bivalves spread all over the world. Pallas described populations of this species from the Caspian Sea and Ural River first in 1797. Reference [1,5,32,33]

The species from the family of *Dreissenidae* did probably not survive in every invaded area. Albeit, *Dreissena polymorpha* was present in Europe before the last glaciation and then bounded in some basins of Eastern Europe in the post-glacial period until the 18th century. In the early 19th century the mussel was already found in the Blatic Sea and then further discovered in the heart of northern Germany. At the same time, the mussel was established in the United Kingdom. The extinction of *Dreissena polymorpha* was then favored all over the original European area. In the 1980s, however, the mollusk was introduced into the Great Lakes area [1,33].

Even though probably already introduced two years earlier, attached to anchor chains or through ship ballast water, the species was discovered for the first time in June 1988 in Lake Saint Clair near Detroit [34].

Within two years, by 1990 the zebra mussel afflicted Lakes Michigan and Huron and within seven years after its arrival in North America the Mussel spread to eighteen American states and two Canadian provinces [35,36]. Current known presence of *Dreissena polymorpha* is in the following US States: Arkansas (AR), Connecticut (CT), Illinois (IL), Indiana (IN), Iowa (IA), Kansas (KS), Kentucky (KY), Louisiana (LA), Michigan (MI), Minnesota (MN), Montana (MO), Mississippi (MS), Nebraska (NE), New York (NY), Ohio (OH), Oklahoma (OK), Pennsylvania (PA), Tennessee (TN), Virginia (VA), Vermont (VT), Wisconsin (WI), West Virginia (WV). In Canada *Dreissena polymorpha* is known to be present in the two Canadian provinces Ontario (ON), Quebec (QC) [37].

The zebra mussel was also ones colonized the Aral Sea. However, increasing salinities and reduced lake area led to the vanishment of the species there [38,39].

Dreissena polymorpha is native in the Mediterranean Sea, the Black Sea and the states of Romania, Turkey and Ukraine. The species is considered introduced in all other states of current presence without any exception. Current state in 2020 suggests that *Dreissena polymorpha* is present in 33 Countries and in 33 North America and Canada respectively [23]. Most countries are European.

Older theories suggest that Zebra Mussels mainly invaded western states due to attachment on chains and ballast water of ships. Nowadays, boats, personal watercraft and related equipment transported from infested to uninfested waters are rather considered as a major factor [15], nonetheless even before turn of the millennium Weinstein and Cohen , already found Zebra Mussels attached to trailered boats entering California [40]. Also migrating blue catfish (*Ictalurus furcatus*) transport live adult *Dreissena polymorpha* through their gut when the mussel was consumed and digested in cooler water (<21.1ºC) [41].

5. BEHAVIOR

Long viability of *Dreissena polymorpha* is one of the causing factors of its worldwide spread. Zebra Mussels can survive around 18 days under damp conditions. Thus, survive an oversea journey attached to the hulk of a ship or in the ballast water [5]. However, other aspects such as spreading through hitchhiking by attaching to hard surfaces of boat hulls, trailers, etc. from one water body to another are important for their distribution as well.

5.1 Attachment to Substrate

Dreissena polymorpha lives in dense aggregations, byssal attached to hard surfaces [42].

Since byssal formation is mostly vital for Zebra mussels, they produce byssus even when they suffer from bad physiological condition or in the presence of toxins [43]. When conditions allow ideal attachment, *Dreissena polymorpha* attach to substrate with about 1-2 Newtons [44]. However, values might differ. Sometimes measurements concerning Zebra Mussels are conducted with their relatives, the quagga mussels *(Dreissena rostriformis bugensis),* resulting in more promising results. As expected, larger individuals attach to substrate with more strength than smaller individuals. Attachment can be further divided into two phases. In the first phase byssal threads are produced ranging 30-60 resulting in increased attachment strength. In the second phase, both the attachment strength stays equal and byssal threads are either not, or slowly produced. Final number of byssal thread ranges between 70 and 80 after three weeks. [45,46,47].

5.2 Detachment and Movement

Their behavior also mainly differs from the one of Unionids. Zebra mussels sometimes voluntary leave their attachment sites. In general, substrate quality, influence of light, hypoxia and effluents from crushed conspecifics, water movements, temperature, and predation influence attachment. Voluntary detachment of Zebra Mussels has already been assessed, leading to the assumption that the Mussels benefit from actively searching new sites which might increase viability. However, this behavior is still rather rare, since detachment means new byssal threads must be formed when the new site is reached, resulting in a high energy cost. This behavior would further increase the chance of being susceptible of predation or water movements. Rizepecki et al. (1993) found that small mussels are frequently observed when climbing up aquarium walls [42].

However, when detached the mussels crawl by use of their wedge-shaped foot. This behavior is more common with adult zebra mussels.

When searching for another site, whether voluntary or due to loss of substrate, *Dreissena polymorpha* can move or crawl, respectively with a rate of up to 48 cm/h [48].

5.3 Colony Formation and Valve Motions

Their ability to sense conspecifics and search for these individuals causes large colony formations.

Zebra mussels usually live in colonies with more than 100 individuals. Sometime, a single Unionid can be infested by 10000 individuals.

A reason for aggregation is the better protection of predators, albeit this behavior makes the mussels grow slower and decreases their condition for reasons of waste accumulation, hypoxia and food depletion [49].

Mussels open their valves for respiration and feeding. These functions are controlled independently by lateral cilia and latero-frontal cirri on their gills.

Mussels open their valves usually most of the time, especially *Dreissena polymorpha* when filtering water. However, mussels are sensitive in terms of ascendancies, resulting in different periods of time when the valves open or close. Especially chemical toxicants or stress response are reasons for mussels to close their valves [50,51].

6. NATURAL ENEMIES OF *Dreissena polymorpha*

Natural enemies of *Dreissena polymorpha* include, turtles, fish and crayfish (Orconectes rusticus) [52] and migratory waterfowl, further known is the consumption of pelagic larvae by copepods and coelenterates, and consumption of attached mussels by leeches, crabs. A total 176 species are known to be natural enemies of *Dreissena polymorpha*., further considered are parasites (34 species) and competitive exclusion (10 species) [15].

However, predation is likely to have a much greater effect on *Dreissena polymorpha* populations reduction. [53,54]

Migratory waterfowl have a large but temporary impact on zebra Mussels in the Great Lakes area [54]. Most of the research in North America has focused on predatory birds and fish as the main predator of *Dreissena polymorpha*. Predator impact differs from continents. Most of the natural enemies of *Dreissena polymorpha* inhabiting Europe are not present in North America [15].

In the following only few predators are discussed.

6.1 Crayfish

With high population densities, reaching (>18 adults/m^2) and biomass (<680 g/m^2) in lakes and streams, crayfish pose a potential threat for Zebra mussel populations. *Orconectes propinquus*, *Orconectes virilis* and *Orconectes rusticus*, have distributions that overlap the distribution of zebra mussels in the U.S. and Canada. Streams with high to moderate density of crayfish will therefore confine Zebra Mussel invasions and decline zebra mussel density. This hypothesis has been tested by Perry et al. revealing that Zebra Mussel density was 58% lower in crayfish enclosures [52].

However, crayfish feeding activity on zebra mussels would be most effective in the early life stage of zebra mussels to diminish populations in the first place. But Love and Savino (1993) detected that crayfish would certainly choose rainbow trout eggs over those of zebra mussels, since they have a lower benefit/cost ratio [55].

6.2 Turtles

The ability of recognizing and crushing mollusks makes turtles an ideal predator for Zebra Mussels.

Especially map turtles, with their large skull length to carpace length ratio and masticatory surface, are considered best traits for crushing mollusks. Map turtles (*Gramptemys geographica)* feed on the Eurasian zebra mussel. Not much time is required for them to recognize and utilize Zebra Mussel as prey. Serrouya et al. (1995) assessed map turtles eating *Dreissena polymorpha* up to an size of 32 mm. However, individuals larger than 25 mm are consumed remarkably slower [56]. Further research has shown that map turtles are even likely to consume zebra mussels in the presence of their conventional prey: the prosobranch “faucet snail” (*Bithynia tentaculata*). Nonetheless, for reasons of energy profitability, as with crayfish, map turtles will eventually consume *Bithynia tentaculata* over *Dreissena polymorpha*.

6.3 Migratory Waterfowl

Dreissena polymorpha pose an abundant food source for several species of diving ducks. In the Area of Lake Erie at Point Pelee, Ontario, diving ducks reduced zebra mussel biomass by 57% during the period of heaviest feeding [54]. In Germany biomass reduction of zebra mussels in Lake Constance is known to be 97%.

Diving duck species known for feeding on Zebra Mussels are Lesser Scaup *(Aythya affinis)*, the pochard *(aythya ferina)*, tufted duck *(Aythya fuligula)*, Common Goldeye *(Bucephala clangula)* and diving rail, the Australian coot (Fulica atra) [57].

However, diving ducks do not have continuous effects on zebra mussel population. Nonetheless, temporary effects are outstanding.

6.4 Endosymbiotic Organisms/ Parasites

Great effort was put into understanding the ecological interrelationships of *Dreissena* *polymorpha* bivalves during the 19th Century. The two most common reported obligate parasites are ciliates and trematodes [15]. However, little effort was put into trematode infections of Zebra Mussels and how theirs symbiotic relationships with endosymbiotic organisms works. A survey study from Laruelle et al. (2002) poses significant insights [58]. Whereas Zebra Mussels collected from Europe showed infestations by three families of digenetic trematodes (Bucephalidae, Gorgoderidae, and Echinostomatidae) and one family of aspidogastrean trematodes (Aspidogastridae), *Dreissena polymorpha* samples from the United States did not show trematode infestation [58]. However, *Bucephalus (Digenea: Bucephalidae)*, *Phyllodistomum* (Digenea: Gorgoderidae), *Echinoparyphium* and *Echinostoma* (Digenea: Echinostomatidae) remain the most commonly occurring trematode genera as parasites of *Dreissena polymorpha*. [15]

Further remarkable is the fact, that all trematodes were identified to the lowest taxonomic level.

Bucephalus polymorphus and *Phyllodistomum folium* from the specimens of the Bucephalidae and Gorgoderidae were the only two species, confirmed as zebra mussel parasites in the study from Laruelle et al. (2002) [58]

Usually, heavy infection of *Bucephalus polymorphus* leads to host castration, since the entire gonadal space is often occupied by the sporocysts. The parasites reside in host connective tissue and is mostly present in the gonads of the host, where infection and sporocyst proliferation takes place. Infestations on *Dreissena.Polymopha* result in the gonads to be seriously affected. Nevertheless, bucephalids in zebra mussels and in unionid bivalves in general, may not be lethal [58]. When affected, *Dreissena polymorpha* can employ a special mechanism of self-defense in some cases. The mussel can encapsulate the trematode in layers of calcium carbonate, located in the gonads.

Phyllodistomum folium cause sporocysts solely in the branchial sinuses, the gills. They develop between outer and inner epithelial layers. Zebra mussels infected with *P. folium* occur with one third less dry weight than uninfected individuals. This is because the trematode has direct access to nutrients contained with the hemolymph, since they occur between those two sinuses. However, another cause might be impaired respiratory and feeding functions, since the gills can be deformed when the infection is already advanced. The impairment in the gills caused by *P. folium* may be lethal in some cases but is not officially confirmed yet.

6.5 Competitors

Zebra Mussels are most often the dominant species in their habitat. However, there are 11 organisms (e.g. amphipods, algae, bryozoans, hydrozoan coelenterates, and other bivalves) capable of excluding *Dreissena polymorpha* from substrate. The most effective organisms are sponges, posing serious threat to Zebra Mussels. They can kill and overgrow Zebra Mussel populations easily especially on vertical surfaces, however, as with the other organisms, they are fouling organisms too, leading to no substantial change for the eco system. [15,21]

7. *Dreissena polymorpha* INFESTING ECOSYSTEMS

7.1 Ecological Impact

Since zebra mussels attach to hard surfaces with their byssal threads they can cause biofouling, similar to that found in marine mussels. The expansion of the zebra mussel within North America has resulted in new physiological and ecological challenges. This may have further consequences once the bivalve returns to Europe [5].

Unionids plan an utterly important role in particle dynamics, nutrient cycling and sediment mixing. Thus, a loss of this species would inevitably cause impairments in aquatic ecosystems in North America, which are habitat to Unionids [59].

The unioniforme families contain at least 180 genera and about 800 species. This order is characterized by the unique parasitic larval stage on the gills, fins or the body of a particular host fish. These freshwater bivalves are suffering a very high rate of extinction, with about 37 species considered presumed extinct in North America alone. The level of endangerment and extinction facing these animals is primarily the result of habitat destruction, modification or invasive mollusk *Dreissena polymorpha* [14,60,61].

Already in 1998, the freshwater mussel order *Uninioda* was the most imperiled faunal group in North America. Since the early 1990, the Zebra Mussels has been spreading all over the

Mississippi River basin, leading to extraordinary high extinction and endangerment rates of impaired mussels. Over 60 endemic mussels are threatened of global extinction by the invasive mollusk [13].

Zebra Mussel invasions can extirpate native mussel populations within a rate of 4-8 years, if density of *Dreissena polymorpha* exhibits more than 3000 individuals pers square-meter.

Illinois and Ohio River showed induced high rates of mortality, connected to the high density of Zebra Mussels in the affected areas.

Comparing the loss of species shows that an invasion of the Zebra bivalve accelerates regional extinction rates 10-fold, leading to an estimated 12 % of species lost in the Mississippi River Basin per decade [13].

Especially Unionidae bivalves are susceptible for *Dreissena polymorpha* infestation. The mussels borrow their anterior portion of their shell into substrate with their foot. The posterior region of the shell remains exposed to the water column, being an ideal surface for *Dreissena polymorpha* to settle [62]. The nonselective Zebra Mussels will attach to Unionidae Mussel shell with their adhesive byssal threads. In some cases, up to 10000 individuals will settle on the shell of one Mussel from the family of Unionidae, [63,64] reaching a colony weight of up to 17 times the mass of the unionid itself [31]. Thin and alate species of unionids are affected much more by zebra mussels and thus decline faster when infested, in comparison to mussels with more inflated, rounded shells which can survive longer under *Dreissena polymorpha* [62].

7.1.1 *Dreissena polymorpha* can affect oviposition of bitterling

Bitterling fish (*Rhodeus amarus*) usually choose Unionids as a location of choice to place eggs. However, when Unionids are strongly infested by Zebra mussels, bitterling will lay their eggs in Zebra Mussels, which makes egg development impossible [65].

Also, Zebra mussel impair boat engines and shipping. Their fouling increases fuel consumption and fouling burdens can sink mooring buoys.

Further their enormous filtering capacity makes *Dreissena olymorpha* capable of diverting energy flow from planktonic to benthic food web. Hus phytoplankton populations, as food to many other species, can very well be depleted by populations of *Dreissena polymorpha* in shallow areas.

7.1.2 Pollutant accumulation in *Dreissena polymorpha*

Freshwater bivalves with high filtering capacities are always susceptible for pollutant accumulation in their flesh. Especially Zebra Mussels with their enormous filtering capacity are often connected with the accumulation of both organic and inorganic contaminants.

Dreissena polymorpha have the potential to change contaminant cycling [66].

Especially, PAHs :fluoranthene, pyrene, chrysene, benzo(a)anthracene, PCB Aroclor 1248, As , Cr and Ba accumulate in Zebra mussel flesh, posing serious harm to organisms feeding on them (e.g. waterfowl) [67].

Further noticeable is metal accumulation in, *Dreissena polymorpha* making the species interesting for monitoring use since, mussels play due to their ease of collection, widespread distribution, relatively sedentary habit and suitable size, a major role in monitoring aquatic contaminants worldwide. When seasonal effects of accumulation or metal pollution of rivers is required, *Dreissena polymorpha* can be utilized as a bioindicator. Their high filtering capacity and thus uptake and bioconcentration of toxic chemicals, or freely dissolved, nonpolar, hydrophobic contaminants, favor their use [68,69,70].

A research study from Kwanetal et al. (2003) further suggests along with a statement by Ion et al. (1997) that mussels could provide stronger signals than adult fish to evaluate areal pattern of contamination in the flora and fauna of a river system. However, these studies refer to the aquatic system of the lower St. Lawrence River [71,72].

The direct absorption of compounds from water is the fastest way for contaminant accumulation in Zebra Mussels or Bivalves in general, since contaminants incorporated in particles must first uptake the adsorbed substance (desorb) from the particles and then diffuse through the gut lining into the mussel-tissue, prior to assimilation [73,74].

Therefore, *Dreissena polymorpha* are of great use for the assessment of contamination in an aquatic system.

7.2 Economic Impacts

Not estimated a single time until the mid-1990s, *Dreissena polymorpha* has a great impact on specific parts of industry concerning water [62]. The US-Shellfishery annually exports thousands of metric tons of harvested mussel shells to Japan for the ubiquitous pearl industry in this country. However, due to species extinction by *Dreissena polymorpha*, substantial economically losses occur, exceeding an annual value of $40 million US. Also, *Dreissena polymorpha* will not be able to replace commonly mussels, harvested for their shells, since the shell of Zebra Mussel is thin and lacking nacre. Thus, not suitable for commercial exploitation [13].

Their bio-fouling activity make zebra mussels a major concern. Water intake pipes are clogged, piles on under water structures are fomed, corrosion gets accelerated and navigational buoys are sinked by *Dreissena polymorpha* [4]. Even though predictions reach as high as $1 billion dollars, a twenty-year model of the economic impact of *Dreissena* polymorpha assessed a total loss of $244.1 dollars in the US-economy alone [4].

Incidentally, the greatest impacts of *Dreissena* polymorpha are recognized in the drinking water treatment and electrical power industry. A research study by Connelly et al. reveals estimated cost of $267 million for the total economic cost for electric generation and water treatment facilities in the period between 1989 and 2004 [75]. And the Central Arizona Project, an organization managing Arizona's single largest renewable water supply, deplored that an infestation by *Dreissena polymorpha* would increase operation and maintenance costs to estimated four or five million dollars annually [15].

According to the Department of State in 2009, maintenance of pipes clogged with zebra mussels costs the power industry up to $60 million per year and temporary shutdowns due to insufficient water flow can cost over $5,000 per hour [76].

However, to the best of our knowledge, there is no precise data or predictions for the economic impact of *Dreissena polymorpha* in recent years (2015-20). Therefore, further study should be conducted to estimate the latest amount of economic loss and economic impact in the future.

8. *Dreissena polymorpha* AND *Dreissena rostriformis bugensis* CONTROL

Both the fast spreading and the extraordinary quick invasion of *Dreissena polymorpha* and *Dreissena rostriformis bugensis* in aquatic systems, conduits and raw water dependent infrastructure makes the control of this species utterly difficult but necessary.

The most common control method in North American facilities dealing with infestation in their water systems, is the usage of chlorine and other types of chemical biocides [32]. For instance, US Patent 5,209,934 was granted May 11th, 1993 suggesting that Zebra mussels can be controlled using chlorine and bromide salt solution at concentrations of 0.05 to 10 mg/l [77]. An European Patent EP 0457439B1, granted March 8, 1994 suggests to control *Dreissena polymorpha* using dimethyl ammonium halides [78].

Chemical methods meet existing water pollutant discharge regulatory limits but could lead to negative long-term impacts.

Biological contorl is another approach to minimize the spred of *Dreissena polymorpha* and *Dreissena rostriformis bugensis* spread. This means, releasing natural enemies with the assumption that this will contain the nonindigenous pest to levels below economic and/or ecological thresholds [79]. This approach, however, will not lead to the expected results when applying to *Dreissena polymorpha*. This is due to their enormous reproductive potential and the lack of natural enemies in the first place. However, as mentioned with migratory waterfowl earlier in this paper, birds can have significant, but only temporary effects on Zebra Mussel populations [54].

Selective toxic microbes may be an effective attempt of biological control, having microbes' function as a highly selective pesticides. Toxic microbes have already been applied to controlling invertebrate pests in North America and all over the world [80].

Daniel.P. Molly suggest that, from more than 700 bacterial strains, North American isolate of the bacterium Pseudomonas fluorescence i.e., strain CL0145A, is capable of effectively killing *Dreissena polymorpha* at a temperatures range between 5°C and 27°C. Bacterial cells destroy the mussels's digestive gland [15]. Solely this strain has special toxic characteristics and is therefore lethal to *Dreissena polymorpha*. A U.S. Patent 6,194,194 for the control of Dreissena species was granted February 21, 2001 [81].

US patent application 2020/0068903 A1 filed February 8th, 2019 suggest the usage of chlorophyll at a level of at least 10 µg/l to 200 µg/l as a control mechanism for killing, preventing or inhibiting the growth of *Dreissena polymorpha* and *Dreissena rostriformis bugensis* [82].

A more technical approach is to control bivalves is Ultraviolet (UV) radiation which is commonly used for disinfecting in drinking water and waste water applications [doelle]. US Patent 6,149,343 granted November 21, 2000 to Lewes and Whitby suggests using UV light at a wave length of 254 nm and an intensity of at least 0.1 W sec/cm² to control *Dreissena polymorpha*, *Dreissena rostriformis bugensis* and other bivalves [83].

Controlling Zebra Mussel in open Water is even more difficult and to there is currently no commercially control method available.

There is also no single method effective enough to control *Dreissena polymorpha* and *Dreissena rostriformis bugensis* and other invasive species in all situations. However, biological control methods within an integrated pest management strategy poses a reasonable possibility [15].

Dreissena polymorpha and *Dreissena rostriformis bugensis* for instance are hard to remove from a surface once infested. Most U.S. States dealing with infestation have control measures supported by state laws in place for recreational equipment such as boats trailers, cars, waders and fishing equipment that are capable of spreading invasive species from waterbody to waterbody.

These control measures include checking and examination of any boating and fishing equipment, see Fig. 2, and gear (kayaks, paddles, trailer axels, boats, trailers, motor propellers, license plates, etc.) for invasive species followed by removing the invasive species after use as well as disinfecting of equipment that cannot be dried by soaking the equipment in 60°C (140°F) hot water.

Dreissena polymorpha for instance are difficult to detach from the surface once infested. They need to be killed first with 60°C (140°F) hot water ore steam and then be removed by brushing or pressure cleaning at a provided contamination site [85]. Fig. 3 shows removed mussel material in a disposal area.

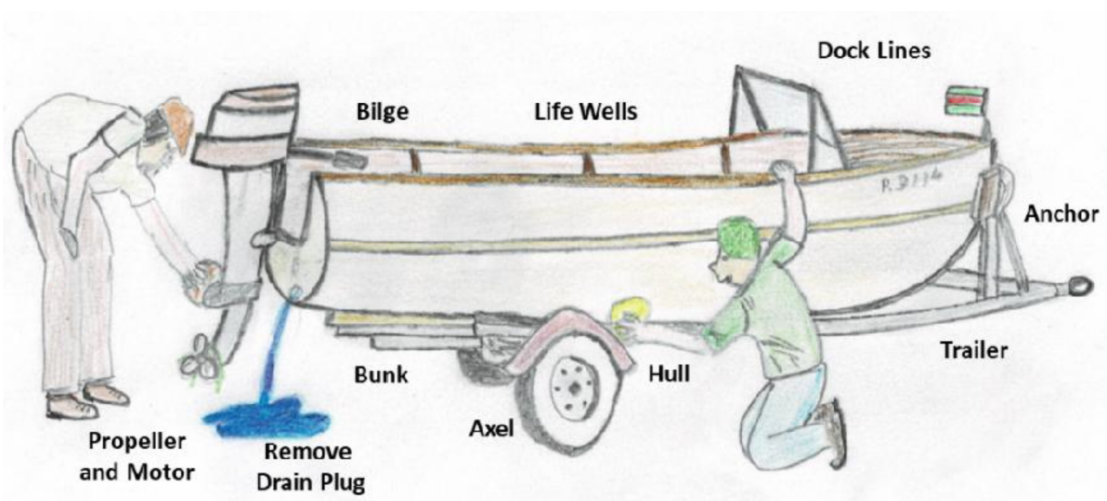

Fig. 2. Boat inspection and cleaning [84]

Fig. 3. Removed Mussels at Disposal Site [86]

9. ZEBRA MUSSELS FOR WASTEWATER TREATMENT

Zebra Mussels have an enormous filtering capacity of about 5 to 400ml/bivalve/h. Further interesting is the fact that they occur with high population density with more than 700000 individuals/m^2 [7].

They produce feces and pseudofaeces which contain suspended particles and contaminants that cannot be used as a food source and are rejected by the mollusk. Settling these pseudofeaces could lead to a removal of column bounded pollutants from the water. Zebra Mussels are also able of reducing algal density and of emerging contaminants, such as pharmaceuticals and drugs of abuse, from wastewaters, too [9].

Already a study in 1983 by Piesik pointed out, that *Dreissena polymorpha* is able to remove nutrients from eutrophic waters. Since then, further studies have confirmed this hypothesis and demonstrated the filtering capacity of this bivalve. Controlled breeding of *Dreissena polymorpha* could be an opportunity for an alternative treatment of polluted freshwaters [87,88,89,90].

US Patent 5,628,904 granted in May 13, 1997 suggests a process for wastewater (WW) treatment using *Dreissena polymorpha.* The patent only suggests a treatment process, but no details of the effluent are given [91].

Using *Dreissena polymorpha* bivalve for wastewater treatment does not required induced energy, since the mussels feed on the waste. They won't cause further waste and the method is much less expensive than common wastewater treatment systems. For treating the wastewater of 100 people, a reactor solely one cubic meter in size and 2000 to 3000 mussels are needed [92].

In 2003, the German microbiologist Barbara Ral strongly considered the advantages of *Dreissena polymorpha* as a chance to improve wastewater treatment plant (WWTP) effluent streams using *Dreissena polymorpha* with the invention of the "ZebraFilter", which was patented in 2002 [93]. According to the patent, 3,000 Zebra Mussels can clean about 100l/h of WWTP effluent to nearly portable water quality removing up to 95% of bacteria and viruses. The influent water quality should have a ammonium level below 8 mg/l and preferably between 0.24 to 0.28 mg/l at a operational temperature between 10°C and 25°C, a dissolved oxygen content of 5mg/l and a pH between 7.7 and 8.7. In addition, *Dreissena polymorpha* needs to be set dry for 1 to 2 hours two times a day.

The microbiologist had already recognized the potential of *Dreissena polymorpha* during her time at university and then founded the ZebraFilter GmbH. Her aim is to include Zebra Mussels sustainably to wastewater treatment [92].

10. CONCLUSION

Freshwater mussels, mollusks without a head and a single foot for crawling are beautiful creatures and allow broad variety of aspects for research. However, from the 927 species in 179 genera some bivalves draw more interest than others. North America, harbouring the most diverse freshwater mussel fauna on earth, as home to approximately 300 species and subspecies generates interest for scientific research concerning mussels. But among the great diversity of bivalves is also the notorious Dreissena polymorpha. Dreissena polymorpha,the zebra mussel is a biofouling pest infesting all kinds of aquatic ecosystems in freshwater. The bivalves with a life span from 2-19 years harms both other mussels from the order of Unionidae as well as organism feeding on phytoplankton. With a size below 5 centimeters the tiny mussels still have great impacts, rapid spread of the mussel has been facilitated by their high fecundity of up to one million eggs per female. They have an utterly distinct life circle. They attach to hard surfaces with byssal threads with about 1-2 Newton. However, their ability to sense conspecifics makes them form extraordinarily large colonies of sometimes about 700000 individuals/m2. Their bio-fouling activity make zebra mussels a major concern. Water intake pipes are clogged, piles on under water structures are fomed, corrosion gets accelerated and navigational buoys are sinked by *Dreissena polymorpha*, causing estimated cost of $267 million for the total economic cost for electric generation and water treatment facilities in the period between 1989 and 2004. Since *Dreissena polymorpha* is mostly already the dominant species and there are very little predators feeding on *Dreissena polymorpha* (e.g. turtles, fish, migratory waterfowl) biocontrol of Zebra Mussels is difficult and nearly impossible without posing further threat to the surrounding environment with the use of chemicals. Even though toxic microbes, unique biochemicals functioning as highly selective pesticides are considered as a possible environmentally friendly method.

Nonetheless, when carefully considering their filtering capacity, Zebra Mussels could be very well utilized for biological wastewater treatment systems. Nonetheless, their invasiveness in the larval stage makes practical application without further spreading and invasion of nearby river or lake systems nearly impossible. Effective methods to stop spreading without harming the eco-system need to be found. Albeit, further research should also address the topic of testing non-invasive mussels for wastewater treatment and practical importance. What is given through *Dreissena polymorpha* is an extraordinary possibility that has to be used effectively in the future. More research needs to investigate the mussel, and deliver most recent research on the mollusk and possible methods for its control, use and the economic impacts and costs caused by the mussels in recent years.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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