The decline in populations of freshwater mussels in Australia (Family Unionidae)

Overview

Figures

1.0 Introduction

It is becoming increasingly apparent that climate change is significantly affecting habitat deterioration and loss, causing similarly diminishing populations and, often, near-complete loss of freshwater shellfish (Jones & Byrne, 2014; Cowie et al., 2017; Bohm et al., 2021). However, local conditions may also contribute to other detrimental effects on the habitats of these particular animals (Galbraith et al., 2015).

Freshwater molluscs are one of the keystone species found in freshwater systems, and their increasingly diminished populations affect water quality and the nourishment of other dependent species within their habitats. This depletion is identified as “loss through extinction, isolation and disturbance” by anthropogenic interference (Baillie et al., 1996; Lydeard et al., 2004).

The most significant of the disturbances contributing to species loss in aquatic habitats is the temperature increase due to climate change; this is not unique to Australia but reflected in other parts of the world (Lopes-Lima et al., 2014). This loss was reflected more than two decades ago in the IUCN Red List of Threatened Species cited in Baillie et al. (1996), commenting that molluscs had gained “the dubious honour of having the highest number of documented extinctions of any significant taxonomic group.”

Freshwater molluscs, according to Smith (1979), Walker et al. (2014) & Vaughn & Hollein (2018), “are filter feeders that perform critical ecological functions and impact aquatic ecosystems by nutrient and energy recycling.” According to Vaughn & Hollein (2018), freshwater bivalves can be described as “dominant filter feeders, which increase water clarity and light penetration, stimulating macrophyte growth and adjacent habitats; they increase the abundance of benthic insects and shellfish are considered as ‘sentinels of environmental change’”. The effects experienced by aquatic ecological connectivity that have suffered disturbances contributing to this situation have also been exacerbated by water flow interventions such as the construction of dams and weirs, river flow regulation, habitat alteration and loss, often with the spreading of invasive organisms, pollution and climate change. This also indicates concern for associated flora and fauna to be considered in efforts to be made in biodiversity conservation (Crook et al., 2015; Dudgeon et al.,2006).

In understanding how to achieve sustainability in the indicated decline in mollusc populations, this essay discusses the identity of the Family Unionidae (bivalve mussels) to give perspective to species distribution and abundance, their importance to the ecosystem through crucial ecosystem processes, including a description of the community dynamics, and the possible and sometimes probable causes of declination. This will then be followed by a discussion of how the current situation may be mitigated and the possible routes to follow for the future of these animals through the conservation of existing habitats and provision of anthropogenically designed habitats where and when considered necessary.

2.0 The Family Unionidae

This family of freshwater mussels is the largest group in the order of Unioida. In Australia, there are 18 species, most of which are unique to this country. Their usual habitats are on the bottom of both lotic and lentic environments, settling in the middle or lower sections of slowly moving streams and avoiding fast-flowing rivers (NSW DPE, 2018). Winhold (2004) cites Smith (2001), who describes the Unionidae as acephalic, "usually with the beak (the elevated portion of the dorsal margin) slightly anterior...The species in this family have a foot rather than a byssus, fibrous structures found in other mussel families...the inhalant aperture (opening in the posterior end of the mantle border where water enters the mussel) of Unionidae has unbranched papillae (bumps)." Because of these relatively small apertures, this animal has to rely on a habitat free and clear of excessive siltation to ensure its process of filtration and ecosystem nourishment. Individuals vary in shape and size and are mainly large and of a brown to black colouration. "Adult individuals can range from 30 to 250 mm" (pp. 3 -5).

Life cycles begin as an obligate parasite called a glochidium that attaches itself to the gills of a fish. This occurs when the mussel releases larvae from its gills, where they attach themselves to the gills of a proximate fish. This attachment triggers a tissue response from the fish that forms a small cyst in which the larvae reside. It feeds by breaking down and digesting the tissue of the fish within the cyst. On achieving a juvenile stage, it detaches and burrows into the stream or lake substrate and completes its growth to maturity; it can live up to 40 years (NSW DEP, 2018). This relationship also indicates the necessity of a healthy fish population to ensure the ongoing life cycle of mussel populations.

3.0 Importance to the ecosystem (including humans)

Historically, aquatic animals are often central to human connections to freshwaters by "providing an important food source and a focal point for culturally significant events, ceremonies, and intergenerational teachings about the natural world" (Cristancho & Vining, 2004). Strong et al. (2007) & Lopes-Lima et al. (2021) also offer data on the global diversity of the main groups of freshwater molluscs identifying the relative position in which freshwater mussels in Australia are placed. In this geographical context, for example, many of the middens in northwest Victoria extend up to 400m. Two aquatic molluscs, members of the order Unionoida, prevalent in these middens were the river mussel *Alathyria jacksoni* and the snail *Notopala sublineata. Alathyria Jackson* appears as a usual human prey species, with the smaller gastropod *Notopala sublineata* collected as a by-catch (Garvey, 2015, p.1).

Freshwater mussels in the order Unionoida are long-lived, sedentary, infaunal, suspension-feeding bivalves and may spend their adult life in dense mussel beds. Mussel beds provide biogenic habitat, modify sediment, filter water, and store and recycle nutrients (Atkinson & Vaughn 2014, p. 4). To this end, they play an essential role in biogeochemical transformations. They are recognised as keystone species, "improving habitats for other species, and indicator species important in assessing the health of the ecosystem"(USGS, 2019).

3.1 Biogeochemical transformations

Mussels act as nutrient transformation sites supporting the rest of the food web and altering nutrient cycling. As indicated in Figure 1., as mussels feed, ‘they remove phytoplankton, bacterio-plankton and detrital organic matter from the water column, metabolise them and excrete dissolved nutrients back into the water, and deposit organic nutrients to the sediment as faeces and pseudo-faeces” (Vaughn & Hollein, 2018). This, in turn, resupplies nutrition to phytoplankton populations which are considered to be “the major

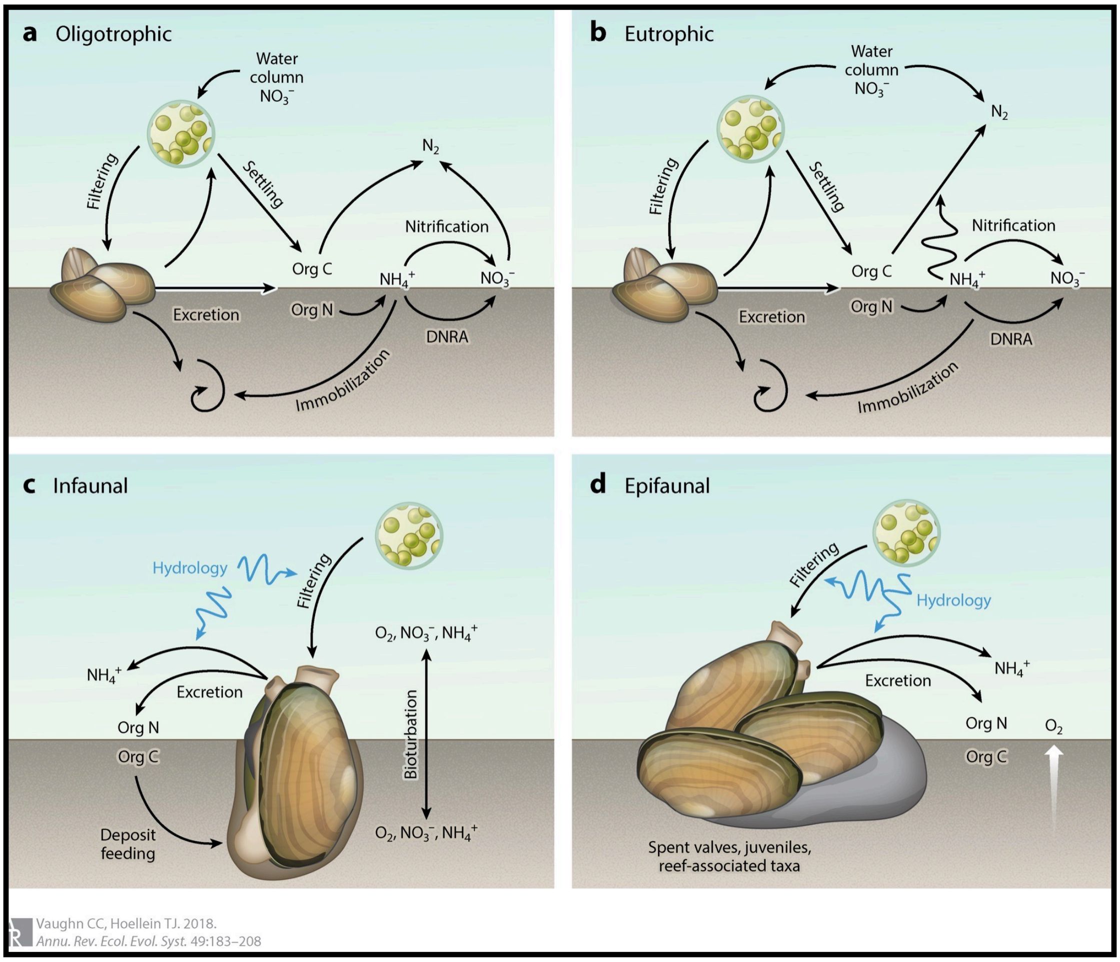


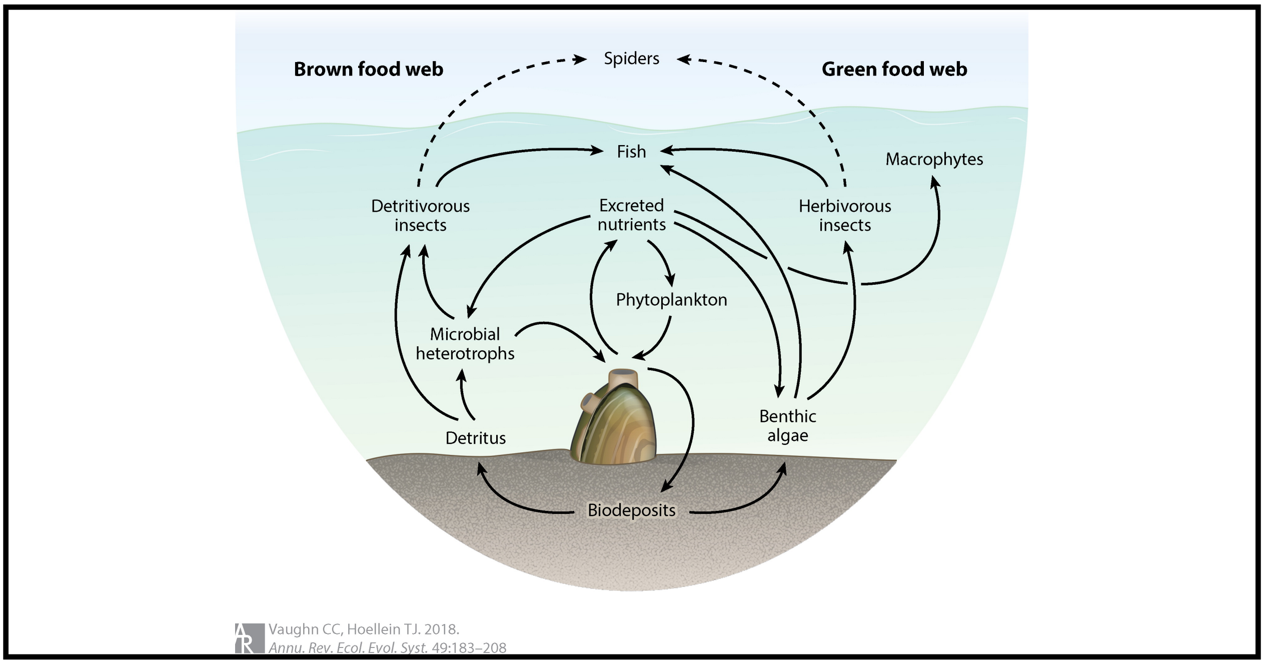
Figure 1. Biogeochemical transformations associated with bivalves in oligotrophic, eutrophic, infernal and epifaunal conditions. Fluxes include filtration, settling, excretion, immobilisation, mineralisation, ammonium efflux, nitrification, hydrology, bioturbation, deposit-feeding and sediment oxygen concentrations. (Adapted from Vaughn & Hollein, 2018).

primary producer in aquatic ecosystems, supplying much of the bacterial carbon demand (BCD, the sum of bacterial production and bacterial respiration)" (They et al., 2014). Figure 1. also indicates the movements of carbon (C), Nitrogen (N) and oxygen (O_2) but neglects to indicate the direction of phosphorous (P), which, although in large concentrations provokes eutrophication, is essential but also a growth-limiting nutrient in aquatic systems (Roy, 2017). Furthermore, "Phosphorus has a major impact on algal food quality, and herbivorous consumers are subjected to significant food quality variation of algae, which they respond to by modifying their life history strategies and feeding behaviour" (Li et al., 2022). All of these elemental cycles are reflected in the trophic levels represented in the dynamism and status of the freshwater mussel communities.

3.2 A microcosm of symbionts - the freshwater mussel community

The Freshwater mussel is an omnivorous animal that feeds on phytoplankton, algae, detritus, and zooplankton (Vaughn et al., 2008). The mussel is a keystone species of the community, with the community itself reflecting a symbiotic web of mutualism, commensalism and predation. This is seen in its structural pattern indicating biodiversity and habitat heterogeneity, reflecting its species richness.

As indicated in Figures 2. & 3., a considerable array of organisms depend on, yet contribute to, the stability of this communal web: phytoplankton, benthic algae, microbial heterotrophs, detritivorous insects, herbivorous insects, macrophytes, spiders, fish and terrestrial predators. With the short food chain indicated in this community, it offers dynamic stability where, alongside the mussel, phytoplankton also could be deemed a keystone species in that a diminished abundance would impact community structure and possibly result in biodiversity loss. This community destabilisation is therefore sensitive, in particular, to pollution from fertiliser run-offs and pesticide applications.



Vaughn CC, Hoellein TJ. 2018.
Annu. Rev. Ecol. Evol. Syst. 49:183–208

Figure 2. Pools (terms) and fluxes (arrows) are associated with freshwater mussels in riverine food webs. Mussels feed on suspended seston and excrete and biodeposit nutrients that stimulate autotrophic and heterotrophic production. This results in increased secondary production of herbivorous and detritivorous insects, which supports in-stream fish production and riparian predators (Adapted from Vaughn & Hollein, 2018).

The importance of the interconnections within this community follows both the rivet and redundancy models for the maintenance of community viability. Examples of the rivet model in this context could be evidenced in the reduction or loss of phytoplankton due to herbicidal pollutants introduced into the streamflow or the isolation of fish used as hosts for the mussel larvae. The loss of one of these species could have a cascading effect on other species and possibly lead to the extinction of the community.

At the same time, supporting the redundancy model of this community, many benthic algae and microbial heterotrophs can be replaced by other species, maintaining communal integrity. Samples of these organisms are seen in Figure 3. This also appears to follow the organismic or Clementsian view of the community concept in that it is composed of a dominant species (the mussel) with other species co-adapted to live in association with it. This could be described as a closed structure. “Considering the uncertainties and

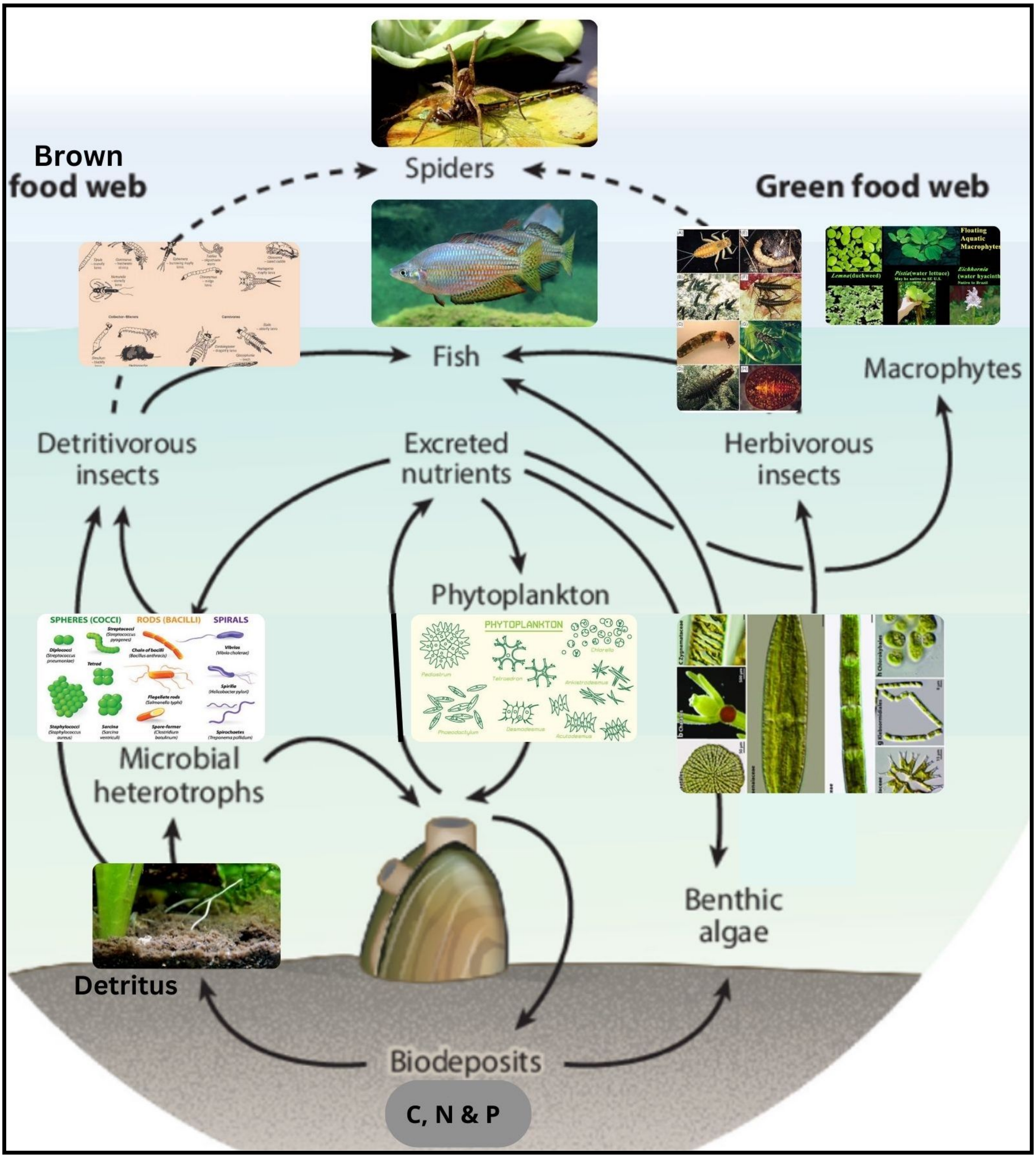


Figure 3. Modification of Vaughn & Hollein's (2018) illustration of trophic/guild members of the freshwater mussel community

Credits: Aquatic spider - https://australian.museum/learn/animals/spiders/water-spider/; Benthic algae - 50211878_Evolution_and_Diversity_of_Plant_Cell_Walls_From_Algae_to_Flowering_Plants/figures?lo=1; Detritivorous insects - https://www.ecologycenter.us/species-richness/detritivores-and-specialist-microbivores.html;Detritus - https://aquariumscience.org/index.php/6-2-1-detritus-explained/;Freshwater mussel - https://austsilvers.com/freshwater-mussels/;Herbivorous insects - http://what-when-how.com/insects/aquatic-habitats-insects/;Heterotrophic bacteria - https://microbenotes.com/classification-of-bacteria/;Macrophytes - Aquatic macrophytes in the tropics - https://www.pinterest.com.au/pin/415246028124546419/; Phytoplankton - https://www.pinterest.com.au/pin/213076626099260894/; Rainbow fish - https://www.dreamstime.com/stock-photo-melanotaenia-boessemani-aquarium-image49035391 complexities in the relationship between biodiversity and ecosystem services, policy decisions should have a significant ‘insurance’ bias toward functional groups in which there is little or no redundancy” (Ehrlich & Walker, 1998, p.1). This suggests that concern should be emphasised in decisions not only regarding the mussel, a keystone species, but also the interconnectedness of its symbionts “to maximise the maintenance of ecosystem resilience” (ibid. p.1)

The feeding guilds within this community may give more clarity to the reader when appreciating the mix of species contained within each grouping, as indicated in Figure 3. This further shows degrees of interspecific interactions between guilds where competition promotes niche partitioning and predation reduces competitive exclusion.

3.3 Mutualism

In green or photosynthesis-based food webs, as indicated in Figure 2. & Figure 3., mussels consume phytoplankton and algae, and subsequent nutrient excretion improves benthic primary production and plays a critical role in algal species composition (Atkinson et al., 2021). It can then be seen to give back nutrition to the organisms it feeds on. This enhanced primary production supports higher in-stream secondary production of aquatic insects and other primary consumers (Howard & Cuffey 2006, Spooner et al. 2013).

3.4 Commensalism

Organic energy and nutrients stored in consumers can subsequently be exported to the terrestrial environment, for example, by emerging aquatic insects (Vaughn 2010), thus demonstrating that this “food web enhancement is due to mussel-derived nutrients whereby other species are fed with no direct benefit or harm to the producer.” As indicated in Figure 2. & Figure 3., green and brown food webs may play similar roles in the inorganic nutrient provision and influence the production of microorganisms through this commensal relationship and then provide secondary invertebrate output to herbivorous and detritivorous insects. Mussels in brown food webs supply both inorganic and organic nutrients and energy via faeces and pseudo faeces to detritivores. Biodeposit particulates also may leach dissolved organic nutrients, which heterotrophic microbes can use (van Broekhoven et al., 2015).

3.5 Parasitism

The movement of fish as hosts is vital for maintaining mussel population dynamics. As shown in Figure 4., the mussels begin their lives with the

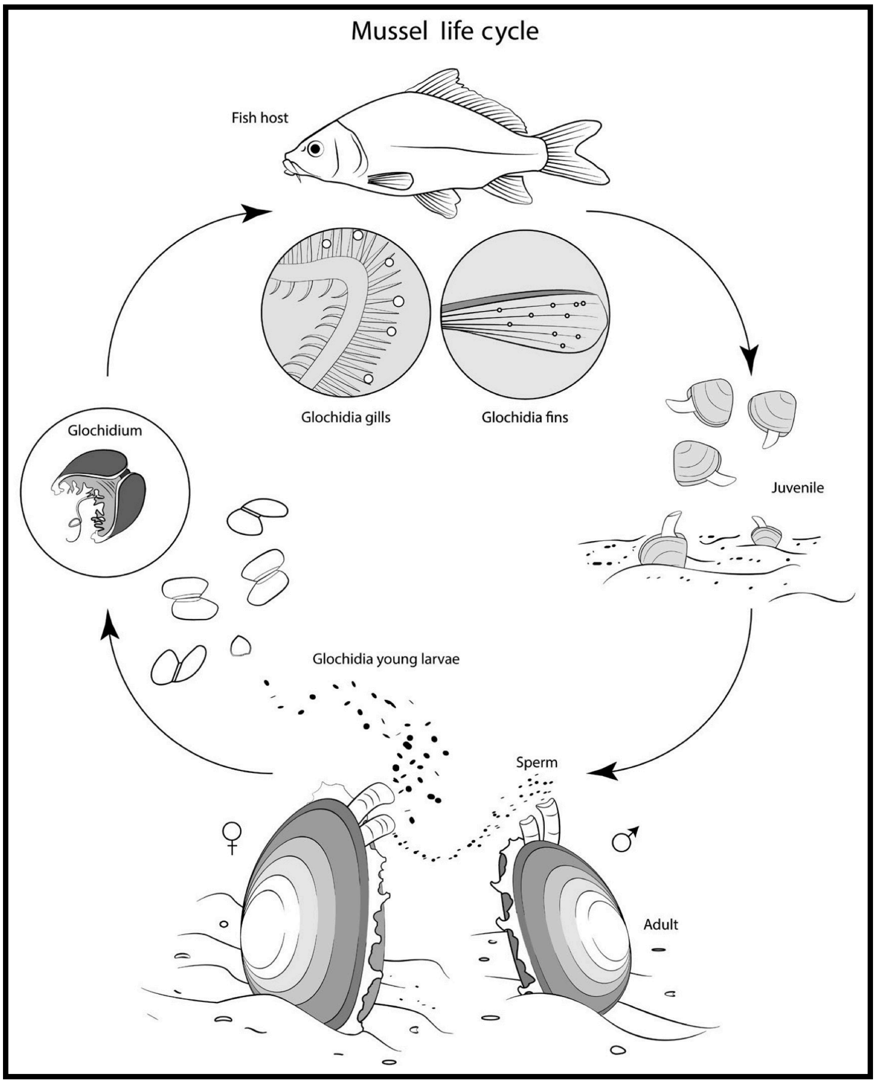


Figure 4. General scheme of the freshwater mussels' life cycle. Courtesy Marcogliese, D.J., 2008.

female taking in sperm from the male and brooding the fertilised eggs in her marsupia, a specialised section of her inner gills. These are then released into the water as glochidia that attach themselves to resident fish species' gills and fins and begin this part of their life cycle as obligate parasites. The encystment of the glochidia, when in place, occurs as the tissue of the fish grows over them. When sufficiently mature, they drop into the sediment and begin the remainder of their life cycle (FMCS, 2016). But parasitism can also work the other way. For example, the European bitterling (*Rhodeus amarus*) parasitises freshwater mussels by laying its eggs in the mussel's gills (Reichard et al., 2010).

However, these relationships may be thwarted without a sufficient and appropriate fish population due to stream flow deviations and artificial barriers. “Barriers to movement can therefore result in significant ecological and evolutionary consequences through poor dispersal, isolation, increase in inbreeding and loss of genetic diversity, making populations more vulnerable to extinction” (Porto-Hannes et al., 2022); not all fish are accepting of glochidia. However, many other problems lead to declining freshwater mussel populations and displacing their attendant symbionts.

4.0 Reasons for the decline

There is considerable literature regarding the global demise of freshwater mussel populations, the majority of which regards the observed patterns of decline resulting from anthropogenic disturbances such as that emphasised by Spooner et al. (2013), describing the poorer physiological conditions of freshwater mussel populations in catchments adjacent to increase agricultural production (p.12). There is also the not-so-evident consideration of other potential issues where data indicates contributions of parasitism and disease to the decline of freshwater mussels (McElwain, 2019).

Thus there are issues of concern other than the recognised effects of anthropogenic disturbances such as siltation through excessive land use, general habitat destruction, and stoichiometric imbalances in stream flow (Vorosmarty et al., 2000); these further concerns are the pathogens contained in stream flows (Carella et al., 2016). Consideration should also be given to potential diseases and disorders occurring naturally or provoked by anthropogenic disturbances that may exacerbate population declines. These etiological agents, such as parasites and pathogens of freshwater mussels, are relatively understudied compared to those affecting marine bivalves (ibid. p.4).

4.1 Pathogens and diseases

Pathogens and diseases can potentially impact freshwater mussels, but there remains a dearth of peer-reviewed literature regarding this area of concern. This is emphasised by Waller & Cope (2019), who avers “the role of the microbiota and pathogens in mussel health has been understudied and, as a result, their role in mussel decline is unknown”. They also confirm that “pathogens, bacteria, protozoan, and metazoan parasites like trematodes, nematodes, mites, and ciliates are reported to have the potential to decrease the fitness of the host unionid.” These species and their respective hosts are represented in Figure 5.

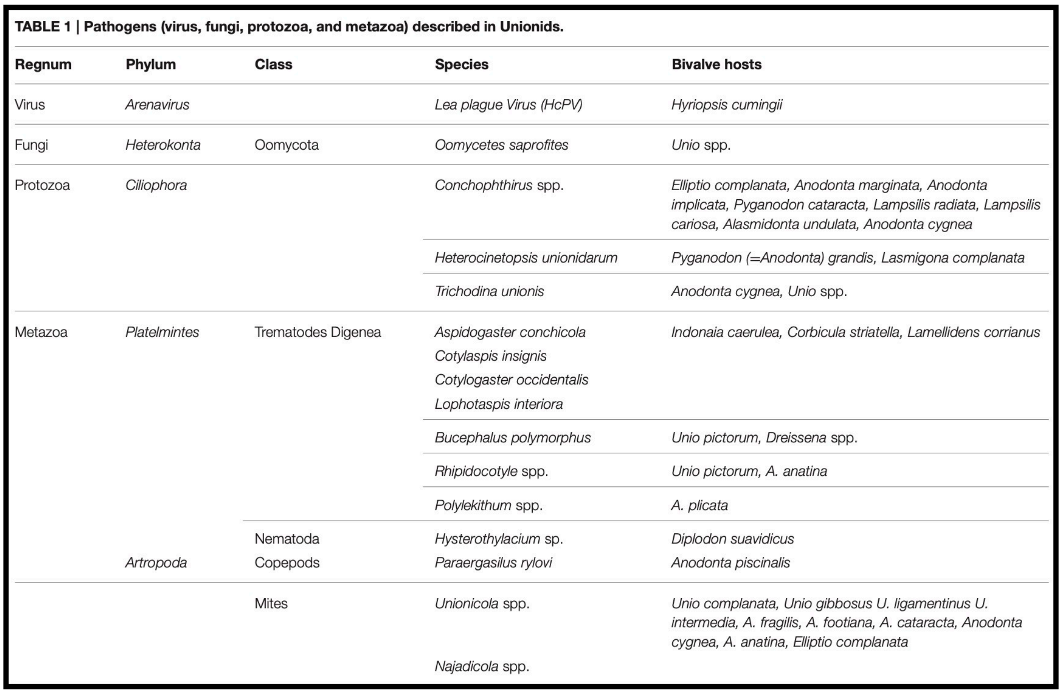


TABLE 1 | Pathogens (virus, fungi, protozoa, and metazoa) described in Unionids.

Regnum	Phylum	Class	Species	Bivalve hosts
Virus	*Arenavirus*		*Lea plague Virus (HcPV)*	*Hyriopsis cumingii*
Fungi	*Heterokonta*	Oomycota	*Oomycetes saprofites*	*Unio* spp.
Protozoa	*Ciliophora*		*Conchophthirus* spp.	*Elliptio complanata, Anodonta marginata, Anodonta implicata, Pyganodon cataracta, Lampsilis radiata, Lampsilis cariosa, Alasmidonta undulata, Anodonta cygnea*
			Heterocinetopsis unionidarum	*Pyganodon (=Anodonta) grandis, Lasmigona complanata*
			Trichodina unionis	*Anodonta cygnea, Unio* spp.
Metazoa	*Platelmintes*	Trematodes Digenea	*Aspidogaster conchicola* *Cotylaspis insignis* *Cotylogaster occidentalis* *Lophotaspis interiora*	*Indonaia caerulea, Corbicula striatella, Lamellidens corrianus*
			Bucephalus polymorphus	*Unio pictorum, Dreissena* spp.
			Rhipidocotyle spp.	*Unio pictorum, A. anatina*
			Polylekithum spp.	*A. plicata*
		Nematoda	*Hysterothylacium* sp.	*Diplodon suavidicus*
	Artropoda	Copepods	*Paraergasilus rylovi*	*Anodonta piscinalis*
		Mites	*Unionicola* spp.	*Unio complanata, Unio gibbosus U. ligamentinus U. intermedia, A. fragilis, A. footiana, A. cataracta, Anodonta cygnea, A. anatina, Elliptio complanata*
			Najadicola spp.	

Figure 5. Pathogens affecting bivalve hosts (virus, fungi, protozoa, and metazoan) (Carella et al., 2016)

The importance of improving this knowledge was emphasised in an earlier work by Marcogliese (2008), who suggests that “climate change will have a profound impact on the spread of parasites and diseases in aquatic ecosystems” and that this will “affect parasite species directly with changes in the distribution and abundance of their hosts”(p.468). Even though what is known about the pathogens and diseases that have the potential to impact bivalve populations, there is significant progress in identifying the molecular mediators of immunity in these animals (Allam & Raftos, 2015). However, from the work of Saavedra et al. (2021), the flow-on effects of antibiotics flushed into aquatic systems have led to emergent strains of antibiotic bacteria leading to the spread of resistance genes. This is a more insidious addition to the already agreed-upon contributors to the declines in mussel population and other biota related to pollution of waterways and other anthropogenic disturbances (Bohm et al., 2021, p.3237).

4.2. Anthropogenic Disturbances

Crook et al. (2015) identify a diverse range of disturbances to freshwater ecosystems caused by humanity. The connections of physical, biological and biochemical pathways that affect biodiversity reflect the necessity for “the ability of freshwater mussels to evolve and adapt under the strong anthropogenic selective pressures such as the physical modification of habitats, pollution, climate change and introduction of invasive species” (Lopes-Lima et al., 2021, p. 2842). Abundance, population dynamics and abiotic tolerances such as changing oxygen and ammonia concentrations are also stressors brought about by anthropogenic modifications of freshwater habitats. Biotic interactions such as host dispersal and predator/prey relationships are also considered volatile, along with human and domestic stock diseases. Crook et al. (2015), Lopes-Lima et al. (2021), and Bohm et al.(2021) provide further extensive data on how changes have occurred in shellfish populations with descriptive evidence of how anthropogenic disturbances have contributed to these changes; these are considered briefly as follows.

4.2.1 Modification of habitats

According to Bohm et al.(2021), residential and commercial development, energy production and mining, invasive and other problematic species, agriculture and aquaculture, and biological resource use are also frequently reported threats to existing habitats. Natural system modification via dams and other barriers also poses a significant threat to freshwater biodiversity. These barriers pose limitations to migratory routes for fish (Dudgeon et al., 2005), and freshwater mussels require fish hosts to complete their life cycle and dispersal (Modesto et al., 2018)

4.2.2 Pollution

The most severe pollutants are those emitted into the atmosphere due to industrial activity. In gaseous form, the greenhouse gases of CO2, CH4, N2O and fluorinated gases contribute to a considerable quantity of emissions affecting the atmosphere; 6,558 million metric tons of CO2 equivalent in 2019 (EPA, 2021). This exacerbates global warming and thus produces higher evaporation and precipitation rates, creating regions susceptible to excessive drought and flooding. This, in turn, makes many terrestrial ecosystems vulnerable to damage and destruction, diverting stream flows and impacting species' survivability. Freshwater environments are also significantly affected by chemical and oil spillages, runoff from agricultural and urban areas that produce anoxic sediment, possibly containing toxic material such as ammonia or sulphides NSW DPE (2018) and creating relatively unlivable habitats for juvenile mussels. Further, more insidious pollution is being found by molluscan ingestion of microplastics (Hollein et al., 2021).

4.2.3 Exploitation

In Australia, no peer-reviewed literature indicates the overconsumption of freshwater mussels for human nutrition. This is not seen as a prime reason for their decline; the primary concern is the alteration of stream water regimes that give prime importance to surface and groundwater withdrawals for human consumption. This can "reduce available habitat, increase water temperatures, and impair mussels' ability to feed, respire, and reproduce" (Golladay et al., 2004; Hastie et al., 2003).

4.2.4 Invasive species

Trade globalisation has increased the invasion of alien species causing subsequent impacts on ecosystems (Gallardo et al., 2018). In Australia, there have been no extreme invasive bivalves like the zebra mussel (*Dreissena polymorpha*) and Asian clam (*Corbicula fluminea*), displacing native species as they have in countries such as North America and Europe (Minchin et al., 2002). However, in the Murray-Darling Basin, the common alien carp (*Cyprinus carpio*) is a predator of benthic invertebrates (Koehn, 2004), including juvenile mussels. There is evidence that carp and goldfish (*Carassius auratus*) may not be hosts for glochidia (Walker et al., 2014); therefore, neither cyprinid is considered part of the mussel's life cycle other than ending it. Drought conditions certainly reduce habitat for mussel ecosystems. On the other extreme, increasing flooding, also due to climate change, allows cyprinids to disperse rapidly to areas where their destructive reach on these and other invertebrates can be expanded (Driver & Harris, 2005).

4.2.5 Climate change

The threat of global climate change is pervasive across the Earth's ecosystems and is also often cited as a significant threat to freshwater biodiversity (Strayer and Dudgeon, 2010). Freshwater mussels are experiencing increased mass mortality events linked to hydrologic drought, and it is essential to understand the resultant ecosystem effects (DuBose et al., 2019). Temperature affects several aspects of mussel physiology and life history, including reproduction, growth, and recruitment of juveniles (Nobles & Zhang, 2011). It is the prolonged duration of high temperatures producing stream depth lowering, thus likely impacting many mussel populations and other aquatic biomes, increasing temperatures rising beyond the threshold limits of some taxa, causing either their extinction or relocation; shellfish, however, do not move quickly. These climatic effects may interrupt the normal flow of nutrients and produce biodiversity loss. This, in turn, can create a feedback loop that further alters ecosystem functioning (Covich et al., 2004).

5.0 Mitigation and Sustainability

The conservation status of the world's freshwater molluscs has been studied by Bohm et al. (2021) to establish the drivers of extinction risk. This is to improve global conservation efforts by establishing what those drivers are and designing ways to combat them. Their research confirms that freshwater mussels are highly threatened and that pollution and modification of natural systems are the most frequently reported threats to freshwater mussels and other freshwater taxa. Their reports suggest the establishment of riparian buffers to minimise run-off, improve wastewater treatment and regulation of pesticide and fertiliser use. Where water is abstracted for agriculture, "infrastructure design and watershed management are necessary for protecting biodiversity" (p.44).

Alongside preserving existing freshwater habitats, Chester & Robson (2013) describe the production of freshwater anthropogenic water bodies as refugia for freshwater biota. They represent the concept of Restoration ecology, which relies on "anthropogenic (human-created) or heavily modified ecosystems to support biodiversity". They also address the range of habitats of this nature, such as Irrigation pipes and canals, rural and urban drainage ditches, transport canals, stormwater retention basins, agricultural wetlands and ponds, large reservoirs and quarry ponds. Their studies show that anthropogenic waterbodies may support freshwater biodiversity and emphasise the need for revised management practices to maximise species biodiversity, particularly concerning the climate change excesses of increasing inundation and prolonged periods of drought.

In Australia, Buelow & Waltham (2020) provide information on the viabilities of restoration of coastal wetland quality and the efforts made in northeast Queensland in the study of bivalve filtration and biodeposition. The provision of artificial habitats indicates a promising step toward the future stabilisation of shellfish populations. Their research findings indicated that bivalve population density frequencies did not differ between artificial and natural wetlands (p.8), but higher biodeposition rates were observed in artificial wetlands (p.11). They then assert that more research is required to determine how the improvements in freshwater mussel population stability affect wetland nutrient budgets and to understand the fate of biodeposits via water flow and whether they contribute to nitrification and denitrification processes. This knowledge is vital to the future of mussel populations and all of the taxa sharing their habitats.

Another relatively recent yet substantial contribution to the reclamation of waterways is the Australian River Restoration Centre. This applies science and the engagement of many stakeholders, including landholders and indigenous communities, in river and riparian restoration. This also results in restoring and providing improved habitats for freshwater mussel populations.

6.0 Conclusion

There is little doubt that this species is critically endangered due to anthropogenic disturbances. However, there has been sufficient research to highlight how these disturbances have arisen and offer methods to mitigate further decimation and provide the potential for population increase. The natural disease and disorders that also affect shellfish populations are not so well publicised.

Unionidae is the most significant order of freshwater mussels, and their habitats are required to be free of excessive siltation to perform their vital tasks of filtration and ecosystem nourishment. They provide transformation sites supporting the food web and altering the nutrient cycling of their habitats. The food web does not isolate itself to the aquatic environment as macrophytes and detritivorous insects are also preyed on by terrestrial fauna. The faecal expulsion of organic nutrients also contributes to various biogeochemical transformations. The decline in freshwater mussel populations discussed was regarding the commonly accepted concerns of anthropogenic disturbances attributed to habitat loss, destruction, pollution and the not-so-well publicised effects of natural disease and disorders.

Mitigation and Sustainability have briefly been mentioned in a global assessment but also give an overview of issues driving extinction risk at broad regional levels. Natural system modification, primarily through dams, and pollution are frequently recorded and likely to impact freshwater molluscs worldwide substantially. As pollution is associated with high extinction risk, it is vital to combat water pollution to ensure healthy mollusc populations. It is suggested that riparian buffers should be established to minimise run-off within impacted areas, improve wastewater treatment and regulate pesticides and fertilisers. Where water is heavily managed for energy generation, flood risk reduction, or is abstracted for agriculture, environmental flows need to be considered in environmental impact assessments, infrastructure design and watershed management to minimise impacts on biodiversity. Identification and monitoring of introduction pathways are required to prevent further detrimental species invasions, as is the protection of critical habitats to avoid extinctions. In addition, research should focus on priorities for the conservation of these species and a better understanding of the impact of threats, such as pollution and climate change.

Incomplete knowledge should not be a barrier to carrying out conservation actions for those species known or thought to be most at risk, but action should take place immediately with what we know. Ecosystem managers may find more significant support for restoring Unionid populations with careful calculations of their ecosystem role in nutrient retention and removal. Also apparent is the necessity for further research on the diseases and disorders affecting these particular populations and the symbionts associated with their ecosystem.

Freshwater molluscs provide invaluable functions to freshwater ecosystems and ecosystem services to humans but are subject to high threat levels. Conservation actions must be increased to safeguard freshwater ecosystems and the species, including molluscs, which depend on them, given the various threats impacting these fragile systems. Optimistically, in Australia, this is seen in developing organisations such as the Australian River Restoration Centre with the support of scientists, landholders, industry bodies, governments, corporate entities and other concerned individuals. Already much has been performed in their endeavours towards freshwater recovery and the potential sustainability of future habitats; this is very encouraging.

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