Aquatic fungi: largely neglected targets for conservation

Aquatic fungi (true fungi and fungi-like oomycetes) are a diverse group that plays a key role in aquatic ecosystems through carbon and nutrient cycling, production of essential organic compounds, food-web dynamics, and energy flow (Gladfelter *et al.* 2019; Grossart *et al.* 2019; Ruess and Müller-Navarra 2019) (Figure 1). They have the ability to shift food-web structure, affect eco-evolutionary processes via biotic interactions, and help in the degradation of pollutants (Harms *et al.* 2011). Despite their critical importance for aquatic ecosystems, some groups such as oomycetes and chytrid fungi are poorly studied, with the majority of species not yet described, and their ecosystem functions not properly understood (Shearer *et al.* 2007; Grossart and Rojas-Jimenez 2016; Amend *et al.* 2019; Grossart *et al.* 2019). Furthermore, aquatic fungi have been completely neglected as potential conservation targets; to date, only a small number of terrestrial macrofungi have been evaluated for the IUCN Red List of Threatened Species (Gonçalves *et al.* 2021; IUCN 2021).

The few studies that address the potential anthropogenic impacts on aquatic fungi almost exclusively focus on risks from the release of fungicides (Dijksterhuis *et al.* 2011; Ittner *et al.* 2018). Fungicides act not only on their intended (mostly terrestrial) targets but also on non-target taxa, compromising the structure of aquatic fungal communities. They adversely affect fungal biomass and diversity, as well as disrupt essential fungus-mediated ecosystem functions such as decomposition (Ittner *et al.* 2018). But fungicides are not the only threat to aquatic fungi and their delicate networks; other pollutants – such as pharmaceuticals, metals, microplastics, and nutrients – can have similar effects (Kettner *et al.* 2017; Amend *et al.* 2019; Grossart *et al.* 2021).

Aside from the risks posed by fungicides and pollutants, almost nothing is known about the other anthropogenic threats that aquatic fungi potentially face (Hervé *et al.* 2018; Grossart *et al.* 2021), although presumably fungi are impacted by the same factors that affect other aquatic organisms, including habitat modification and degradation, biological invasions, and climate change (Figure 1). Habitat modification and degradation may lead to community composition shifts, ecosystem function loss, and (possibly) cryptic extinctions and ecosystem collapse. Invasive alien species may disturb ecosystem dynamics and negatively affect aquatic fungi, for example by contributing to the elimination of plant species that provide leaf litter to specific fungal communities, or through biotic interactions like competition. Climate change may have direct effects on the metabolism, growth, and reproduction of aquatic fungi, as well as indirect effects through alteration of ecosystem functioning, due to changes in water temperature and hydrology.

Besides the risk of species extinctions, aquatic fungal communities can also experience population declines and a reduction or even total loss of key ecosystem functions, which may lead to cascading effects in aquatic food webs. Yet, given the large gaps in knowledge that exist, many cases of ecosystem function losses are likely to remain cryptic (Jarić 2015; McConkey and O'Farrill 2015), hindering implementation of timely and effective conservation measures.

We argue that the conservation of aquatic fungi has not received adequate attention, and that improved understanding of these taxa will be critical for effective and sustainable management and conservation of aquatic ecosystems. Future research efforts should focus on advancing knowledge of the drivers and mechanisms responsible for the substantial decline and/or loss of entire aquatic fungal communities, and on overcoming the primary knowledge gaps, including feedbacks to aquatic biodiversity, networks, and key ecosystem functions.

Conservation of aquatic fungi needs to be urgently recognized as a management priority and incorporated into aquatic conservation frameworks. Aquatic management efforts should focus on both protecting fungal diversity and maintaining their key ecosystem functions, which can be most effectively achieved through ecosystem conservation. Promising management measures also include recognized actions that have proven successful in protecting other components of aquatic communities, such as reducing and banning the import of nutrients and other contaminants; controlling introduction pathways of aquatic invasive alien species; identifying, protecting, and restoring key waterbodies and habitats for aquatic biodiversity; and maintaining ecologically relevant hydrological regimes. Such measures might, however, need to be streamlined and customized to consider the particularities of fungi. It would be also critical to work toward not only adopting strict policies against pollution sources but also developing and applying new, standardized fungal bioassays. Nagai (2018) defined four factors that fungal bioassays should incorporate: namely, that test organisms should be (i) ecologically relevant in terms of their distribution, with a (ii) wide range of taxonomic groups included, which should be (iii) available from publicly available culture collections and (iv) suitable for culture experiments. We propose an additional criterion: that the organisms should (v) represent different functional groups, including biotrophs and saprotrophs (Ittner *et al.* 2018). Such developments are the prerequisite for reaching conservation targets for aquatic fungi.

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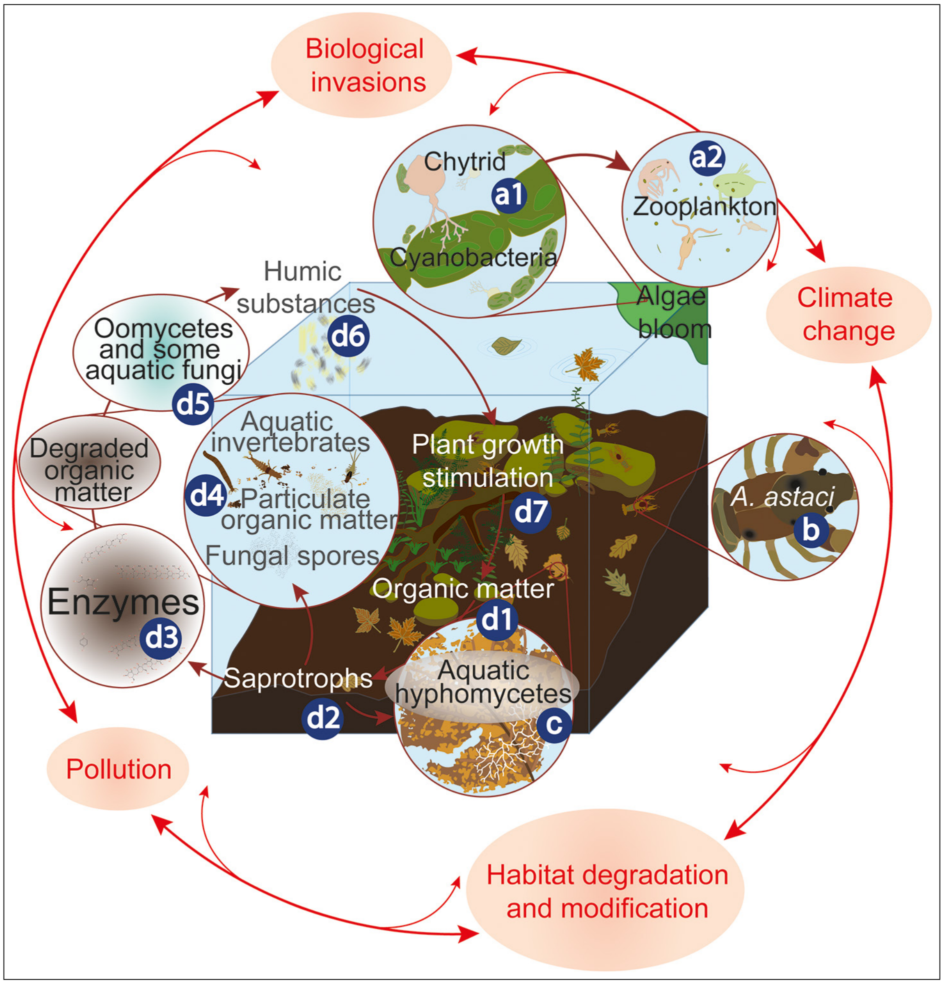

Figure 1. Key roles of and threats to aquatic fungi in freshwater ecosystems, with lowercase letters indicating different portions of the food web, and numbers indicating examples. (a1) Chytrids (parasitic fungi) infecting cyanobacteria and fundamentally controlling algae blooms. (a2) Cyanobacterial particles left over from fungal processing serve as food sources for zooplankton. (b) Control of a crayfish population by *Aphanomyces astaci*, the fungal pathogen associated with crayfish plague. (c) Aquatic hyphomycetes degrading leaf matter at the substrate level. (d1–d3) Enzymatic degradation of organic matter by saprotrophs. (d4) Aquatic invertebrates feeding on particulate organic matter resulting from fungal activity. (d5) Further degradation of organic matter producing nutrient-rich humic substances (d6), which stimulate plant growth (d7). Aquatic fungi can be affected by a range of anthropogenic impacts, including pollution, biological invasions, climate change, and habitat degradation and modification.

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Data Availability Statement

No data were collected for this study.

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Wrapping leaves around flowers and fruits

While conducting field research on ephemeral plants in the Gurbantünggüt Desert (northwest China) in May 2021, we observed leaves of the annual herb *Atriplex dimorphostegia* wrapped around its flowers and fruits. *A dimorphostegia* was the only species that we detected exhibiting this characteristic. This phenomenon is scarcely reported in the literature and may play a particular functional role. The ovate (egg-shaped) leaves of *A dimorphostegia* are subsessile (have small stalks). Both leaf surfaces (top and bottom) are gray–green, but the lower surface is often densely furfuraceous (covered with flaky bits). The functional purpose of this wrapping behavior remains unclear. Succulent leaves might create a barrier to prevent sunlight and sand from directly reaching the flowers and fruits, but leaf wrapping raises other questions. Does leaf wrapping reduce the extent or efficiency of photosynthesis because the leaf orientation is nearly vertical? If the leaves limit the access of potential pollinators to the flowers, is outcrossing affected? Why does this trait remain so rare in desert plant species?

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