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The intertwined lives: phytoplankton, zooplankton, and the fish in aquatic ecosystems

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Abstract

Phytoplankton, zooplankton, and fish form an intricate web of interactions that drive the functionality, productivity, and stability of aquatic ecosystems. These three trophic groups are not only ecologically interdependent but also dynamically responsive to environmental changes. Phytoplankton, the primary producers, is grazed upon by zooplankton, which in turn serve as a primary food source for many fish species. Feedback mechanisms involving nutrient cycling, predation pressure, and climate fluctuations further shape these relationships. This review explores the trophic linkages, energy flow, and regulatory feedbacks among phytoplankton, zooplankton, and fish, emphasizing their collective role in maintaining aquatic ecosystem health. Insights into recent studies on trophic cascades, climate impacts, and anthropogenic pressures highlight the significance of conserving these interconnected.

Keywords: Phytoplankton, Zooplankton, Fish, Trophic level, Producers, Ecosystem

1. Introduction

Three crucial trophic levels namely phytoplankton, zooplankton, and fish interplay in a delicately regulated manner to drive aquatic ecosystems, both freshwater and marine. These elements serve as vital markers of ecological health in addition to sustaining biodiversity and energy flow. Their interactions are essential to the productivity of fisheries, nitrogen cycling, and ecosystem functioning. Phytoplankton are microscopic, photosynthetic organisms that make up about half of the world's primary output and are found at the base of the aquatic food web (Field *et al.* 1998, Kumar *et al*. 2022). Since they are primary producers, they are the first organisms in aquatic food chains to absorb solar energy (Kumar *et al*. 2023, Pal *et al*. 2024). Light, temperature, and nutrient availability are some of the abiotic variables that affect phytoplankton dynamics. Recent research has shown changes in the biomass and organization of phytoplankton communities due to continuing global climate change. Warming trends, for example, have encouraged the dominance of smaller phytoplankton cells, which are numerous but may not be as effective at sustaining fish larvae and zooplankton grazers (Peter & Sommer 2013, Winder *et al*. 2009). Additionally, warming impacts phytoplankton-to-zooplankton biomass ratios, especially in nutrient-enriched lakes, according to a thorough lake study conducted in Sweden (Yan *et al.* 2023).

As a vital link between phytoplankton and fish, zooplanktons occupy the medium trophic level. They comprise a diverse range of creatures that eat phytoplankton and are subsequently eaten by fish, such as copepods, rotifers, protozoans, and cladocerans. Through grazing pressure, vertical migrations, and nutrient recycling, zooplankton play a role in biogeochemical cycling in addition to trophic transmission (Steinberg & Landry, 2017). Significantly, warming modifies the size distribution, metabolic rates, and phenology of zooplankton, potentially causing misalignments with fish hatching times and phytoplankton blooms (Beaugrand *et al.* 2003, de Senerpont Domis *et al.* 2013).

In this triad, fish make up the higher trophic level; many of them are zooplanktivorous when they are young. The availability and timing of suitable zooplankton prey have a significant impact on their recruitment and growth increment (Cushing 1990).

According to Edwards & Richardson (2004), phenological mismatches that cause fish larvae to hatch either too early or too late in relation to zooplankton abundance might result in low survival rates. In freshwater and marine systems, this phenomenon-also referred to as the "match-mismatch hypothesis"-has garnered empirical support (Durant *et al.* 2005).

The delicate synchronization between these trophic levels can be upset by environmental changes, according to recent studies. Warmer spring temperatures, for example, may induce phytoplankton to bloom sooner. However, fish larvae may face food scarcity at crucial developmental stages if zooplankton does not shift correspondingly due to differing life cycle constraints (Thackeray *et al.* 2010, Halsband & Hirche 2001). Recruitment failures in commercially significant fish species, such as herring and cod, have been associated with such mismatches (Platt *et al.* 2003).

Zooplankton influence nutrient dynamics and carbon sequestration in addition to direct feeding connections. By transferring organic matter from surface waters to deeper levels through diel vertical migration, numerous zooplankton species support the biological pump and carbon export (Longhurst & Harrison, 1989). Both preserving the oceanic carbon balance and reducing atmospheric CO2 depend on these activities. In the meantime, zooplankton communities are governed from the top down by fish populations. Changes in zooplankton size, content, and structure brought about by selective predation can change the grazing pressure on phytoplankton (Carpenter *et al.* 1985). Depending on the degree and kind of fish predation, this cascade effect has the potential to either maintain or collapse food webs. For instance, it has been demonstrated that the eradication of piscivorous fish sets off trophic cascades that lead to phytoplankton overgrowth and a decline in water quality (Jeppesen *et al.* 1997). Aquatic food webs are supported by the intricate trophic relationships between fish, zooplankton, and phytoplankton. These interactions enable energy to go from the primary consumers to higher levels of trophic hierarchy, ensuring ecological functionality and biodiversity (Figure-1)

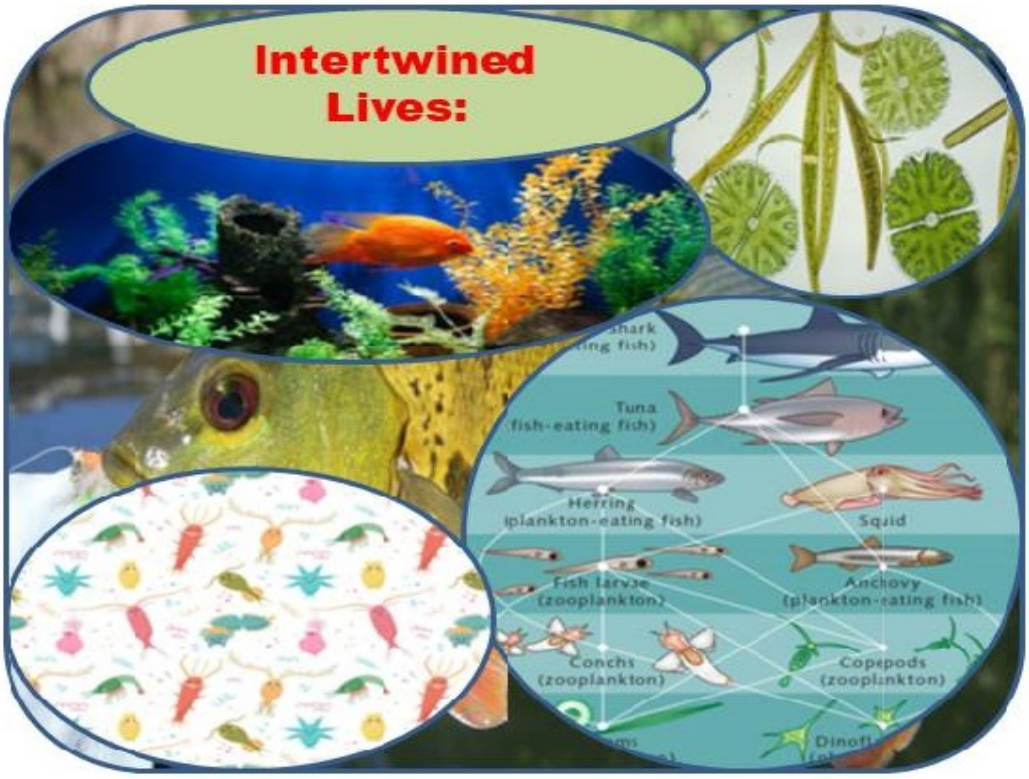

Fig. 1. A interconnecting life of phytoplankton, zooplankton, and the fish in aquatic ecosystems.

The equilibrium of these interactions is being shifted by anthropogenic stressors such pollution, overfishing, eutrophication, and climate change in addition to natural dynamics. Eutrophication promotes the growth of phytoplankton, which frequently results in toxic algal blooms that compromise the integrity of the food web (Paerl & Otten 2013). Zooplankton feeding and reproduction have been reported to be hampered by microplastic pollution (Cole *et al*. 2015). An increasing issue, underwater noise pollution influences zooplankton behavior and may have minor but considerable effects on predator-prey interactions (Duarte *et al.* 2021). Moreover, trophic imbalances are frequently caused by the introduction of alien species/exotic fish species (Mayank & Dwivedi 2017, Dwivedi *et al*. 2018, Tripathi *et al*. 2024). For instance, Bythotrephes longimanu's (spiny water flea) invasion of the Laurentian Great Lakes upset the natural zooplankton populations and had a domino effect on fish diets and nutrient flows (Bunnell *et al*., 2011).

Technological advancements have transformed the monitoring and modeling of these complex trophic connections. Plankton and fish community composition can be detected non-invasively using tools like environmental DNA (eDNA) (Bohmann *et al*. 2014). Furthermore, trait-based models, which provide a higher level of precision than conventional taxonomic methods, are being utilized more and more to forecast how zooplankton will react to environmental changes (Litchman *et al*. 2013). Artificial intelligence has recently been used to automate the interpretation of plankton images, increasing the speed and precision of species identification and biomass estimations (Irisson *et al.* 2022).

Aim of the Review

The purpose of this review article is to-

1. Describe the mechanisms by which fish, zooplankton, and phytoplankton interact at different trophic levels.
2. Summarize the latest findings on aquatic ecosystem feedback loops, biomass shifts, and phenological mismatches.
3. Evaluate how these processes are being altered by anthropogenic forces and climate change.
4. Draw attention to how new technologies can be used to track and model these linkages.
5. Offer guidance for sustainable fisheries, conservation, and ecosystem management in the face of rapid environmental change.

2. Phytoplankton: Primary Producers

Aquatic food webs are supported by small photosynthetic organisms called phytoplanktons. Through the biological carbon pump, they play a crucial role in controlling atmospheric carbon and account for almost half of the world's primary production (Field *et al.* 1998). Light availability, temperature, nutrient concentration (particularly nitrogen and phosphorus), and grazing pressure all affect the growth and make-up of phytoplankton communities (Reynolds 2006, Kumar *et al*. 2020, Pal *et al*. 2023).

Diatoms, cyanobacteria, dinoflagellates, and green algae are among the several groupings whose ecological roles and nutritional worth differ from those of zooplankton. In contrast to cyanobacteria, which frequently produce less appetizing or even hazardous blooms, diatoms are usually rich in essential fatty acids and are easily eaten by copepods (Brett & Müller-Navarra 1997).

3. Zooplankton: Primary Consumers

The primary grazers of phytoplankton are zooplankton, which includes copepods, rotifers, protozoans, and cladocerans (like Daphnia). They are essential for recycling nutrients and moving energy to higher trophic levels. Phytoplankton dynamics and community composition are directly impacted by the efficiency and selectivity of zooplankton feeding (Lampert & Sommer 2007). Many zooplankton species exhibit diel vertical migration, which aids in their ability to avoid predators such as fish while obtaining surface phytoplankton at night (Zaret & Suffern 1976). Furthermore, careless eating and zooplankton excretion aid in nutrient regeneration, which promotes phytoplankton growth (Sterner & Elser 2002).

4. Fish: Predators and Nutrient Cyclers

Both top-down and bottom-up interactions occur between fish and plankton communities. Sardines and many freshwater species' juvenile stages are examples of planktivorous fish that eat zooplankton, which may change phytoplankton biomass through trophic cascades (Carpenter *et al.* 1985). Benthivorous and piscivorous fish, on the other hand, have distinct effects on the distribution of prey and nutritional dynamics (Tripathi *et al*. 2023).

Fish also recycle nutrients through bioturbation and excretion. In certain situations, their migrations between the benthic and pelagic zones can improve primary productivity by redistributing nutrients (Vanni, 2002). Additionally, the stability and robustness of the planktonic ecosystem can be influenced by the presence or absence of fish (Post *et al.* 2000).

5. Trophic interactions and cascades

Phytoplankton, zooplankton, and fish interact on three levels, which frequently leads to cascading effects. As an illustration of a trophic cascade, an increase in piscivorous fish can decrease planktivorous fish populations, which in turn increases zooplankton biomass and decreases phytoplankton abundance (Carpenter & Kitchell 1993). Environmental factors, species mix, and ecosystem type all affect how strong and which way these cascades flow. In contrast to temperate lakes, limited zooplankton-fish interaction may weaken cascade effects in some tropical systems.

6. Environmental and anthropogenic impacts

6.1 Climate Change: Planktonic species' phenology and metabolic rates change as temperatures rise. Warming tends to favor smaller phytoplankton and zooplankton species, for instance (Winder & Sommer 2012), which could change fish food quality and throw off trophic interaction synchrony.

6.2 The eutrophication: According to Diaz and Rosenberg (2008), nutrient enrichment, primarily from agricultural runoff, encourages phytoplankton blooms, which can cause hypoxia and fish mortality. The species makeup is also changed by excess nutrients, favoring toxic cyanobacterial blooms.

6.3 Over fishing: In both freshwater and marine environments, overfishing can eliminate top predators, resulting in unmanaged planktivore populations, decreasing zooplankton, and increased phytoplankton biomass (Pauly *et al.* 1998).

7. Management and Conservation Implications

In order to manage aquatic ecosystems sustainably, fish, zooplankton, and phytoplankton must all remain in balance. Lake and river restoration has been successful using strategies like biomanipulation and changing fish communities to reduce eutrophication (Mehner *et al.* 2002, Tiwari *et al.* 2016).

Water quality and biodiversity can be enhanced by fertilizer input control and the preservation of keystone zooplankton species. The preservation of the integrity of these trophic interactions requires integrated ecosystem-based management strategies.

8. Conclusion

The cornerstone of aquatic ecosystems is the complex interaction of fish, zooplankton, and phytoplankton, which propels energy flow, nutrient cycling, and food web stability. Fish control plankton populations through predation and nutrient recycling, while phytoplankton, as primary producers, initiate the transfer of solar energy and zooplankton mediate this transfer to higher trophic levels. Both manmade stressors and natural variability can affect this trophic triad. Changes in organism size and phenology brought on by the climate might throw off the synchronization necessary for effective energy transfer. While overfishing eliminates important predators, upsetting trophic cascades, eutrophication changes species composition and encourages toxic algal blooms. These relationships are further complicated by new dangers like noise pollution and microplastics. Our ability to track and comprehend these dynamics has significantly improved because to recent technical developments like environmental DNA, trait-based modeling, and AI-powered picture analysis. When paired with ecosystem-based management techniques like targeted bio-

manipulation and nutrient control, these tools present viable ways to address ecosystem imbalances and guarantee long-term sustainability. In the end, preserving aquatic biodiversity and the functional integrity of aquatic food webs necessitates an all-encompassing, flexible strategy that incorporates ecological expertise, cutting-edge technology, and proactive management.

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