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Aquatic biological invasions exacerbate nutritional and health inequities

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Fish are a critical source of accessible nutrition. However, when non-native species introduced through aquaculture establish in the wild, they inevitably alter the structure of ecological networks. This could have unprecedented outcomes for nutrient and toxin accumulation when aquatic food is consumed by humans, with socioeconomically variable impacts.

Non-native species aquaculture for food security

Aquatic foods (aquaculture and capture fisheries) are considered a cheap and accessible source of animal protein in low- and middle-income countries (LMICs). Nutritional inequities are experienced disproportionately by, and predicted to worsen for, women and children in these regions, rendering safeguarding food security for human health a global priority [1]. International development policies in Asia, Africa, and South America promote non-native species aquaculture for economic growth and human well-being, despite considerable environmental risk, on the premise that non-native species aquaculture will increase access to critical nutrition. Contemporary aquaculture in these regions uses fast-growing strains of non-native species, such as Nile tilapia (*Oreochromis niloticus*), common carp (*Cyprinus carpio*), and Mozambique tilapia (*Oreochromis mossambicus*), and these are favored over native species. However, escapees from *in situ* cage aquaculture, alongside deliberate introductions of non-native species through the aquaculture pathway, are responsible for numerous instances of damaging biological invasions into wild-capture fisheries.

Humans are often overlooked within ecological networks, yet, in Africa, Asia, and South America, they still overwhelmingly function as 'apex predators' in aquatic systems. Safeguarding access to safe and nutritious food is a major international priority, but the impact of biological invasions originating from aquaculture and fishery pathways on human well-being is poorly understood. Although non-native aquatic foods may provide more food [2], they also have the potential to change the quality and safety of aquatic foods through their perturbation of native food webs.

There are well-documented mechanisms of ecological and socioeconomic impacts (both positive and negative) of non-native species [3], but ecological changes that drive socioeconomic impacts are rarely assessed. Here, we demonstrate how integrating network ecology and socioecological feedback loops provides a future research roadmap and sets an agenda to address this knowledge gap in the current One Health framework. Specifically, we must determine how non-native species invasions change nutrient distributions and exposure to toxins for human consumers in fisheries food systems.

Trophic ecology of invasions

Invasions of wild fisheries by non-native species can deplete ecosystem services by reducing native fishery stocks [2]; however, little is known about the nutritional ecology of native versus non-native aquatic foods. When a non-native species establishes in a new area, it can rewire local ecological networks through novel interspecific interactions. For example, competition and predation by non-native invasive species can remove nodes from the food web or cause native species to consume poorer quality resources and contract their trophic niches [3,4]. Non-native invasive species often consume more resources and forage less selectively compared with native species, which can result in biotic homogenization of community traits [4,5]. These mechanisms may also cause changes (positive or negative) in bioaccumulation (i.e., of nutrients or toxins) within individuals or species [4,6] (Figure 1).

Socioecological networks

For humans, and within ecological food webs, nutrient and toxin bioaccumulation cascades through the food web [7–9]. Consuming a greater dietary diversity (or having a larger trophic niche) supports better nutritional health/quality, thus linking organismal nutritional status and human nutrition through ecosystem services [2,4,6–10] (Figure 1).

Reduction in functional trait diversity, driven by biological invasion or overfishing, can correspond to a reduction in nutrient availability in capture fisheries [10]. However, nutrient distribution following perturbation depends on species traits [10]; for example, in Peru, overfishing increased the number of small fish species, which filled the niche of larger, overfished species and maintained fish stocks and fatty acid content, but zinc and iron availability reduced [6,10].

Toxins that remain in the environment, such as heavy metals or 'forever chemicals' [per- and polyfluoroalkyl substances (PFAS)], can accumulation in biota and cause severe deleterious effects on the health of individuals (both animal and human) and ecosystems, with exposure to toxins dependent on which species are consumed (Box 1; Figure 1). In the Amazon, larger bodied,

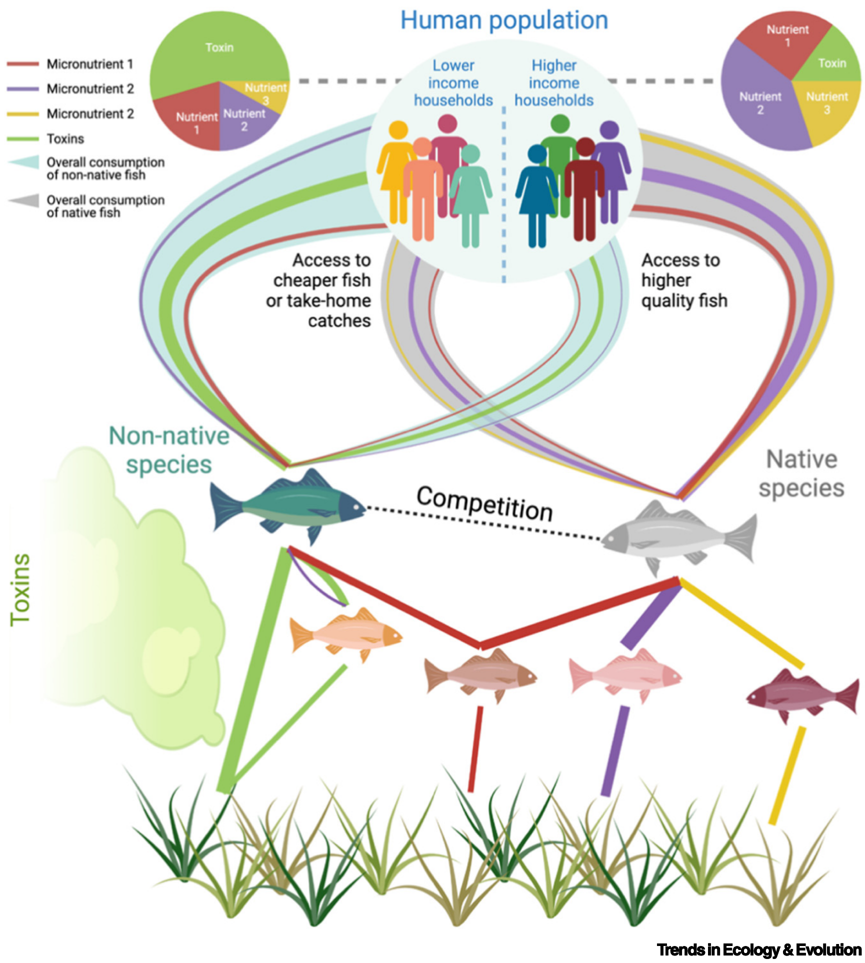

Figure 1. The interactions of fish within aquaculture and fisheries settings represent ecological networks, the structure of which dictates the nutritional content of fish for human consumption. This forms a wider socioecological network, the construction of which may illuminate mechanisms that exacerbate nutritional inequities. Introduction of non-native species, sometimes beneficial for fisheries, can impact native species through not only competition (exploitation, apparent, and interference) as shown here, but also predation and non-consumptive mechanisms, with profound implications for ecological networks and the flow of nutrients through those systems. Access to higher quality fish is often linked to greater household income, which may result in paucity of some nutrients in the diets of people with lower household income, and increased dependence on, for example, lower quality invasive species. The introduction of toxins may disproportionately impact invasive or native species, depending on their physiological tolerances, trophic generality, and wider behavior and ecology, in turn driving exposure of lower income households to changing concentrations of toxins. Created using BioRender (biorender.com).

predatory species are more likely to accumulate higher concentrations of mercury, yet have lower nutritional value [11]. Therefore, the impact of non-native invasive species on food webs has the potential to alter (positively, negatively, or both simultaneously) nutrient availability and bioaccumulation of toxins within fisheries (Figure 1).

Demographic differences in access to fish

Access to fishery resources varies based on the socioeconomic and cultural factors of a given society, determining who can access different fishery species (i.e., large versus small fishes, native versus non-native) and the relative value of each species (Box 1). Inequitable access to fishery resources may exacerbate health concerns, such as malnutrition and toxin exposure, potentially driven by invasive species dominance, despite them sometimes providing higher quantities of food [2,11,12] (Box 1; Figure 1). This may be particularly noticeable in lower income households who cannot access higher value products or a diversity of resources.

Future research directions

Future research in aquatic food systems must strive to construct socioecological networks to link invasive species impacts at the population level to broader outcomes for ecosystem health and human wellbeing [13]. While we provide here a theoretical basis, this practically requires access to comprehensive fisheries monitoring data, household consumption surveys, and a nuanced understanding of community changes and their drivers. These data are sparse, especially in the regions that are most at risk, and should be prioritized through national research campaigns co-led by governance departments related to biodiversity, health, and economic development. Major questions include: what species traits may confer changes in bioaccumulation (nutrients or toxins) in food webs and which non-native and native species are most at risk? How do abiotic and biotic factors moderate the accumulation of nutrients within fishery species? At what scale (i.e., time since invasion or invader abundance) are these impacts (positive or negative) detectable? What are the socioeconomic/demographic drivers of fish species consumption? These may be interrogated through highly resolved interaction data, nutrient/toxin analysis of fishery species across invasion scenarios, and network simulation studies parameterized by laboratory-derived bioaccumulation rates.

To safeguard food security and mitigate nutritional inequities, we must rapidly

Box 1. Mechanisms behind inequitable access to fisheries products and nutritional replacement

In southern Africa, fishing is undertaken by both men and women. However, men usually fish for bigger and more valuable species, whereas women generally fish in shallow waters for smaller, low-value species. The men's catch is either sold in local markets or transported to bigger markets in nearby urban areas [15]. The women's catch is usually retained and consumed at home. This is driven by gender inequalities in decision-making, access to knowledge and equipment, and gendered time demands excluding women from optimal market conditions [15]. Rural households depend on nearby informal markets, which generally sell small and cheap dried fish that are not suitable for export to larger markets in urban areas [15]. Different fishery species are disproportionately used by different subsets of society, resulting in different levels of benefit depending on location, financial capacity, and gender.

Ecological network perturbation by invasive species introductions can alter the nutrient content of species consumed [4]. These ecological effects have the potential to cascade into social networks, but the subsets of society that are most impacted will depend on the social systems in place locally [11–13]. Rural communities closer to water bodies rely on aquatic food for sustenance; therefore, they are likely to be disproportionately affected by non-native species impacts to aquatic food webs and, thus, should be a key focus for risk assessment.

develop capacity for transdisciplinary research, combining concepts from sustainable development practices with ecological theory and socioeconomics, to more carefully guide policies on aquaculture and non-native species introductions. We recommend that aquaculture projects are assessed using time horizons (fixed periods over which a 'project' is evaluated for value gained) to synthesize short- and long-term gains. Determining the stage of invasion at which a change occurs is a key challenge in invasion science and similarly when addressing sustainability issues. Solutions that appear beneficial in the short-to-medium term may exhibit adverse effects over longer durations. Examining the quantity and temporal and demographic distribution of socioeconomic value creation (or loss) is crucial for understanding the dynamic impacts of invasive species. For example, within a defined regional context, a non-native species may initially contribute to substantial short-to-medium term benefits, such as enhanced resource availability or increased economic productivity. However, a longer-term perspective could show a lack of market revenue, loss of ecosystem services, and health-related issues. Such long-term consequences can erode or even reverse the initial economic gains, leading to substantial socioeconomic and ecological costs. Applying sustainability theory to contexts in which non-native species hold socioeconomic value can be a pragmatic and novel approach to appraising the dynamic nature of ecosystem services and the potential for delayed, yet profound, impacts of biological invasions.

Improving our understanding of trophic interactions and the mechanisms by which nutrients and toxins cascade through ecological networks is critical to predicting outcomes for human health and well-being in all food systems [9,10,12,14]. Although we have presented aquatic food webs as the major focus here, it is likely that biological invasions can perturb the provision of nutrients to humans by other food systems, for example, through altering pollinator communities and plant–pollinator interactions [14]. Therefore, policies aiming to support human well-being must consider the socioecological cascades of ecological interactions before implementing interventions, such as promoting climate change-resilient crops or aquaculture/fisheries enhancements. While negative outcomes of biological invasions are presented, the opposite is also possible, whereby a subset of the human population could, for example, gain access to non-native species and gain health benefits. This context and time dependency highlights the need to investigate these socioecological networks across a range of temporal and spatial scales and social contexts.

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Declaration of interests

None declared by authors.

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