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editorial

Increasing risk of migrations through the Panama Canal

For more than a century, the Panama Canal's freshwater Gatun Lake served as an effective barrier against the migration of marine species between the Atlantic and Pacific oceans (Rubinoff and Rubinoff 1968, Ruiz et al. 2009, Ros et al. 2014), but recent developments indicate that this long-standing barrier may now be weakening.

Attention was first raised when never-before-seen euryhaline fishes were observed in the canal (Castellanos-Galindo et al. 2020). Environmental DNA analysis then provided further evidence that marine fishes may be widely distributed within the canal (Schreiber et al. 2023). Now, recreational and artisanal fishers frequently catch marine fishes like snapper (Lutjanidae), ladyfish (Elopidae), and corvina (Sciaenidae) in the canal's lakes (Fig. 1). These rapid changes are raising concerns of an imminent suite of migrations between the Tropical Atlantic and Pacific oceans, with unknown consequences.

We call for enhanced research and cross-institutional collaborations to address this dynamic situation. The ongoing biological and physical monitoring efforts across the canal and marine waters at the canal's entrances must be prioritized and stimulated financially with collaborations across diverse institutions in Panama to reveal the magnitude and pace of these changes. Biological monitoring is critical to provide early-warning information for involved parties across the region (Schreiber et al. 2023) and physical monitoring could help identify the cause of the rapid increase in marine animals inside the canal. These two pieces of information are also needed to develop predictive models about which animals are more likely to tolerate the low salinity and other biological and physical conditions of the canal and pass from one ocean to the other.

Identifying the underlying cause(s) of the uptick in marine species migrations may also offer potential mitigation strategies. For example, if fishes are found to be making use of specific areas of the canal's locks to move between critical areas, physical and nonphysical barriers could be considered as tools to limit migrations. These include electrified, bubble, sound, and strobe light barriers, whose effectiveness improves when used in concert (McIninch and Hocutt 1987, Noatch and Suski 2012, Putland and Mensinger 2019), although some fishes are able to bypass such barriers (Stewart 1981). Water management approaches may also be considered as a tool to limit migrations. If the movement of migrant animals is found to be highly seasonal or diurnal, water exchange between the ocean and the canal via the canal's new water saving mechanism (Kumar 2022) could be timed appropriately to reduce the probability of migrations. However, the Panama Canal is currently experiencing unprecedented low water levels and drought, and climate change is predicted to worsen the situation (Oxford Analytica 2020), meaning that water management approaches designed to limit species migrations may take a low priority. Moreover, any mitigation strategy would likely need to be swiftly implemented to be fully effective.

Given these uncertainties, it would be prudent to begin to explore the possible short- and long-term consequences of interoceanic migrants. The geologically recent formation of the Isthmus of Panama means that closely related taxa of many

Figure 1. A cargo vessel travels from the Pacific towards the Caribbean through the Culebra Cut in the Panama Canal (left). In the last couple of years, the number of marine fishes observed inside the canal has increased considerably to the point that recreational fishing of species like Corvina (*Cynoscion* sp.) is now commonplace (right; photo courtesy "Panama Fishing Trip" tour operator taken at 9.116°N, 79.796°W).

groups can be found on either side (O'Dea et al. 2016), begging the question of how such species will interact if migrations are successful. Cross-fertilization and hybridization is unlikely to be a concern (Lessios and Cunningham 1990), but species may compete leading to potential declines in natives. Alternatively, migrants may become established by occupying vacant niches (e.g., Albano et al. 2021) and the amount of vacant niche space may be surprisingly high given the low functional and taxonomic diversity of both the Caribbean and Tropical Eastern Pacific (McLean et al. 2021) caused by low immigration and high extinction over the last few million years (Leigh et al. 2014). A critical question to ask, therefore, is the degree of functional or niche overlap in animals that occur across the two oceans today. When doing so, it is important to recognize the environmental differences across the Isthmus and how ecologically dominant species in the Pacific side are generally those with feeding and reproductive traits well-suited to high planktonic productivity and high thermal variations, while dominant Caribbean species are well-suited to thermal stability and oligotrophy (but high benthic productivity; Leigh et al. 2014). These environmental differences may place a natural barrier to invasions, but they could also mean that successful migrants will be those that are rare in their native ocean. Niche modelling could help predict the winners and losers and the shape of any resulting novel assemblages (Elleouet et al. 2014), assuming that migrants do not evolve and maintain their fundamental as well as realized niches (Aguilar-Medrano 2018, Liu et al. 2020).

Unlike the Suez Canal, where research began too late to document migrations and quantify the true scale of their ecological impacts on the Mediterranean Sea (Azzurro et al. 2022), there is an unrivalled opportunity here to predict and study interoceanic migrations in real time, explore potential mitigation strategies, and provide valuable forecasts for constituents across tropical America.

Aaron O'Dea [1,2] and *Gustavo A Castellanos-Galindo* [1,3,4]

[1] Smithsonian Tropical Research Institute, Panama. [2] Sistema Nacional de Investigación, Panama. [3] Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany. [4] Freie Universität Berlin, Berlin, Germany.

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