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The Demographic Footprint as a Challenge to Freshwater Ecosystems: A Multi-Stressor Assessment Using the Fish Species Alburnoides bipunctatus

Freshwater ecosystems in Serbia (Central Balkans) are increasingly shaped by the cumulative demographic footprint of human activity, reflecting the ecological consequences of population growth, urban expansion, land-use intensification, and associated environmental pressures. Rivers, as ecologically sensitive and spatially confined systems, are particularly vulnerable to anthropogenic stressors such as pollution, habitat fragmentation, hydrological alterations, and biological invasions. These local pressures interact with climate-driven changes, such as rising temperatures, altered flow regimes, and seasonal mismatches, leading to complex and often synergistic ecological disruptions. Together, these stresors cause structural and functional shifts in aquatic biota, with fish populations being especially affected. This study aimed to disentangle and quantify the spatial manifestation of interacting anthropogenic and climate-related pressures using the spirlin (Alburnoides bi-

punctatus, Bloch 1782) as a model species. Typically associated with oxygen-rich and structurally complex habitats, the spirlin has demonstrated notable persistence in ecologically disturbed river systems, suggesting its potential as both a resilient species and an early-warning indicator of environmental stress. To explore this potential, we applied the ESHIPPOClim model, a composite ecological assessment framework integrating four main components: ES + ILSFP (biological components), HIPPO (anthropogenic stressors), and Clim (climate-related parameters). The model was calibrated using long-term ichthyological and environmental data collected from 2003 to 2021 across a wide range of river sectors in Serbia. Visual analytics, such as facet plots, boxplots, and min–max scaled heatmaps, revealed a consistent upward trend in cumulative ecological pressure. The spirlin's adaptability was particularly evident in sectors with elevated pressure, where high ES + ILSFP scores co-occurred with increased HIPPO and Clim values. This suggests that resilient populations can persist even under substantial and overlapping environmental stress, indicating that such areas may represent spatial thresholds where early biological responses to ecosystem degradation become measurable.These findings underscore the importance of recognizing demographic change not only as a socioeconomic factor but also as a significant ecological driver. The effective management of freshwater ecosystems requires an integrative monitoring framework that encompasses biological, hydrological, demographic, and climatic dimensions to detect ecological tipping points and guide adaptive, evidence-based conservation strategies.

Keywords: Ecological modeling, climate change, demographic footprint on freshwater ecosystems, ESHIPPOClim