

Significance of otolith in freshwater fish migration studies and sustainable fisheries management

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Abstract

Otoliths are the calcium carbonate structures within the inner ear of teleost fish, composed of three pairs - sagitta, lapillus, and asteriscus. These structures grow through the periodic deposition of calcium carbonate and protein layers. Because otoliths are metabolically inert and not subject to resorption, the growth rings (annuli) and incorporated chemical signatures in it remain permanent throughout the life cycle of the fish. As permanent biological archives that begin developing before hatching, otoliths offer an efficient and robust method for biogeographical reconstruction providing critical data for the effective management and conservation of fish populations.

Keywords: Otoliths, sustainability, inland fisheries, migration

Introduction

Otoliths are calcified structures located in the inner ear of teleost fish and are considered the natural data storage tags that record the environmental history of fish. Fish typically possess three pairs of otoliths: one each of sagitta, lapillus and asteriscus. Otoliths grow by the periodic deposition of calcium carbonate and protein layers, forming distinct growth rings. These rings can be daily, seasonal, or annual, allowing researchers to accurately determine the age and growth rate of individual fish. Beyond age determination, otoliths incorporate trace elements and stable isotopes from the water in which the fish resides. Since otoliths are metabolically inert, the trace elements and isotopes they absorb remain permanent. Consequently, they offer a chronological and unaltered record of every environment a fish has encountered throughout its life cycle.

Significance of otolith in fish migration studies

Understanding fish migration is essential for managing populations, particularly for species that occupy diverse habitats throughout their life cycles. Otoliths serve as reliable proxies in these studies; analyzing their elemental and isotopic signatures provides critical insights into fish ecology and life history. Because otoliths begin developing before hatching and are not subject to resorption, they act as permanent biological archives that reflect the ambient water chemistry of a fish's successive habitats. Furthermore, the ability to derive robust data from a limited number of samples makes this an exceptionally efficient method for biogeographical reconstruction.

Reconstructing life histories:

Otolith microchemistry has become a powerful method for reconstructing these movements. Variations in elemental ratios, such as strontium-to-calcium (Sr:Ca) or barium-to-calcium (Ba:Ca), reflect changes in salinity and water chemistry. This allows researchers to distinguish between freshwater, estuarine, and marine habitats used by fish at different life stages. Annuli, the growth rings on the otoliths help validating fish age, and by integrating chemical data with these growth rings, can precisely reconstruct the timing of a fish's migration to new habitats.

Identifying natal origins:

The core of the otolith reflects the water chemistry of the environment where the fish hatched. Comparing this core to known environmental signatures helps identify natal streams or specific spawning grounds. This method is also used to differentiate hatchery-reared from wild fish.

Discriminating fish stocks:

Variations in otolith shape and microchemistry aid in identifying population connectivity and stock structure. Fish populations that appear morphologically similar may originate from different spawning areas or follow distinct migratory routes. Otolith chemical signatures can reveal these differences, helping researchers understand population mixing, dispersal patterns, and recruitment dynamics.

Identifying stress and environmental events:

The chemical composition of otoliths can distinguish between migratory and resident individuals within the same population. Specific trace elements act as proxies for environmental conditions, like elevated levels of manganese (Mn) can indicate exposure to hypoxic (low-oxygen) "dead zones". Oxygen isotopes are deposited in near-equilibrium with surrounding water, allowing to estimate the temperatures experienced by fish at different life stages. Ratios of Strontium (Sr:Ca) and Barium (Ba:Ca) are widely used to reconstruct movements between freshwater and marine environments. Analysis of strontium concentrations has been widely used for tracing salinity history and reconstructing past environmental histories of fish. Ba:Ca is useful for identifying movements between different freshwater habitats or tracking riverine plume environments as it is generally higher in freshwater.

Key techniques

Structural and morphological analysis: In hatchery-reared fish, induced structural marks made by rapid temperature changes during incubation can serve as permanent identifiers to distinguish them from wild recruits. Otolith morphology (outline) can differentiate between distinct stocks or populations that have resided in geographically separate areas.

Otolith microchemistry: Laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) is used to map elements across a sectioned otolith to create a life-history profile while EPMA (Electron Probe Microanalyzer) is often used for 2D X-ray intensity mapping to visualize elemental distribution.

Isotopic analysis: Isotopic analysis of otoliths measures stable isotopes deposited in their calcium

carbonate structure to reconstruct environmental histories. Isotopes provide finer spatial resolution than elemental ratios alone because they are often independent of physiological regulation.

Advantages over traditional tagging

Unlike traditional tagging, which requires catching and recapturing fish, otolith analysis yields comprehensive data from a single specimen. By examining fossilized or archived otoliths, researchers can track the migration of fish from decades or centuries ago. Because they record a lifetime of data from hatching to death, otoliths provide a level of detail unattainable with electronic tags, especially in juveniles.

Significance in sustainable fisheries management

Sustainable fisheries management relies on accurate knowledge of fish population structure, growth, mortality, and habitat use. Otolith-based studies directly support these objectives. Age and growth information derived from otoliths is fundamental for estimating stock productivity and setting appropriate harvest limits. Without reliable age data, fish populations may be overestimated or underestimated, leading to unsustainable exploitation. Otolith studies also contribute to habitat conservation and ecosystem-based management. By identifying essential fish habitats such as spawning and nursery grounds, fisheries managers can prioritize areas for protection, seasonal closures, or habitat restoration. This is particularly valuable in the face of coastal development, damming, climate change, and pollution, which can alter critical habitats and migration routes.

In the context of global climate change, otoliths provide insights into how fish respond to changing environmental conditions. Growth increments can reflect variations in temperature and food availability, while isotopic composition can indicate shifts in water masses and productivity. Long-term otolith records allow to compare historical and contemporary growth patterns, offering evidence of climate-driven changes in fish populations. Such information is increasingly important for adaptive fisheries management. Understanding how climate variability influences migration timing, growth rates, and habitat use helps managers anticipate future changes and develop more resilient management strategies.

Otolith data is crucial for sustainable fisheries management as it helps managers to understand how well different habitats are connected, which areas are critical for specific life stages, differentiate between wild and farm reared stocks and how the changes in water temperatures and environmental stressors affect migration patterns.

Conclusion

Otoliths play a vital role in fish migration studies and sustainable fisheries management by providing accurate age estimates, reconstructing life-history movements, and revealing population structure. Their ability to permanently record environmental and biological information makes them invaluable tools for understanding fish ecology. As fisheries face increasing pressures from

overexploitation and climate change, otolith-based research will remain essential for informed decision-making, conservation planning, and the long-term sustainability of fish resources.

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