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Impact of Climate-Induced Metabolic Stress on the Nutritional Density of Wild-Caught Small Pelagics

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Abstract

Small pelagic fish, including sardines (*Sardina pilchardus*), anchovies (*Engraulis encrasicolus*), and herrings (*Clupea harengus*), serve as critical "nutrient pumps" in marine ecosystems and are primary sources of long-chain polyunsaturated fatty acids (LC-PUFAs) and essential micronutrients for human populations. However, anthropogenic climate change is inducing significant metabolic stress through the twin mechanisms of ocean warming and deoxygenation. This research article synthesizes physiological data, biochemical analysis, and ecological modeling to evaluate how climate-induced metabolic stress alters the nutritional profile of these species. We demonstrate that rising sea surface temperatures (SST) increase metabolic maintenance costs, diverting energy from lipid storage to homeostatic regulation. This shift results in a quantifiable reduction in omega-3 densities and protein quality. Furthermore, the "temperature-size rule" (TSR) and reduced zooplankton quality suggest a future where small pelagics are not only smaller in biomass but significantly less nutrient-dense, posing a direct threat to global food security and neonatal health in fish-dependent regions.

Keywords: Small pelagic, Metabolic stress, Nutritional density, Climate change, Fisheries biochemistry.

Introduction: Small Pelagics as a Nutritional Cornerstone

Small pelagic fish represent roughly 25% of the total global capture fisheries, acting as a vital link between primary production and higher-trophic-level predators, including humans. These species are uniquely valued for their concentration of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are essential for cardiovascular health and cognitive development (Hamilton et al, 2024). Beyond lipids, they provide highly bioavailable iron, zinc, and Vitamin B12, which are often deficient in terrestrial plant-based diets (Golden et al, 2023). However, the nutritional integrity of these "superfoods" is intrinsically tied to their metabolic efficiency, which is currently being disrupted by rapid thermal shifts in the anthropocene (Vucic-Pestic et al, 2025). As ectotherms, their physiological processes are governed by ambient water temperatures, making them highly sensitive to even minor climatic fluctuations (Moyano et al., 2026).

The concept of "nutritional density" in fisheries is increasingly being redefined by metabolic ecology. Traditional management has focused on biomass (tonnage), but climate change necessitates a shift toward monitoring the "nutrient yield" per kilogram of catch. Metabolic stress, defined here as the physiological strain resulting from environmental conditions exceeding an organism's optimal range, triggers a reallocation of energy (Moffett et al, 2025). When fish experience thermal stress, they prioritize cellular repair and cardiovascular maintenance over the synthesis of high-energy lipids. This metabolic "tax" paid to the environment directly diminishes the nutritional value of the fish at the point of harvest (Peck et al, 2024).

The Physiology of Thermal Stress and Lipid Depletion

Ocean warming acts as a potent metabolic catalyst, increasing the basal metabolic rate (BMR) of small pelagics according to the Boltzmann-Arrhenius relationship. As SST rises, the oxygen demand for aerobic metabolism increases, yet the oxygen-carrying capacity of warmer water decreases (Watson et al, 2025). This creates a "metabolic squeeze," where fish must utilize stored triacylglycerols—the primary form of energy storage—to fuel survival rather than growth or reproduction. Research in the Mediterranean has already shown a direct correlation between record-breaking heatwaves and a 15% reduction in the lipid content of European anchovies (Sardà et al, 2026). This depletion is not merely a loss of "fat" but a specific reduction in the structural phospholipids that carry essential omega-3s (Smith and Jones, 2025).

The biochemical pathways involved in fatty acid synthesis are also temperature-sensitive. Higher temperatures typically favor the production of saturated fatty acids (SFAs) over polyunsaturated fatty acids (PUFAs) to maintain cell membrane fluidity—a process known as homeoviscous adaptation (Dittman et al, 2025). Consequently, as the ocean warms, fish tissues become richer in "less healthy" fats while the ratio of Omega-3 to Omega-6 fatty acids declines (Vucic-Pestic et al, 2025). This biochemical shift is exacerbated by the metabolic cost of detoxifying cellular byproducts produced during thermal stress, such as reactive oxygen species (ROS). The energy diverted to antioxidant production further reduces the pool of amino acids available for high-quality protein synthesis (Tanner et al, 2025).

The Temperature-Size Rule and Micronutrient Dilution

A ubiquitous response to ocean warming is the "Temperature-Size Rule" (TSR), where individuals attain smaller adult body sizes in warmer waters. Smaller fish have higher surface-area-to-volume ratios, which facilitates better oxygen diffusion but alters their overall nutritional stoichiometry (Bonnaffé, et al., 2024). Because certain micronutrients like calcium, iron, and zinc are often concentrated in the bones and viscera of small pelagics (which are consumed whole), changes in body proportions directly impact the mineral yield per serving (Golden et al, 2025). Models suggest that a 1°C increase in SST could lead to a 3% to 5% decrease in the mineral density of small pelagic assemblages. This "shrinkage" effect creates a double burden: fewer fish are caught, and those that are caught provide less nutrition (Golden *et al*, 2024).

The metabolic trade-offs associated with smaller sizes also affect the accumulation of vitamins. Vitamin D3 and B12 are often sequestered in the liver and fatty tissues of small pelagics; as these tissues shrink due to metabolic stress, the absolute concentration of these vitamins drops. Furthermore, the accelerated life cycles of "smaller, faster" fish in warm water may reduce the time available for bio-accumulating essential trace elements from their diet (Golden *et al*, 2023; Golden *et al*, 2025). This results in a "dilution effect" where the rapid growth phases under thermal stress prevent the maturation of nutrient-dense tissues. For populations reliant on these fish to prevent stunting and anemia, this dilution represents a significant public health risk (Golden *et al*., 2024).

Trophic Mismatches and Bottom-Up Nutritional Stress

The nutritional quality of small pelagics is largely a reflection of their diet, primarily composed of lipid-rich copepods and diatoms. Climate change is disrupting the phenology and composition of these lower trophic levels, leading to "nutritional mismatches" (Teichberg, et al. 2024). Warmer waters favor smaller, less fatty zooplankton species, which contain significantly lower levels of EPA and DHA. Small pelagics feeding on these "nutrient-poor" prey items are unable to meet their own metabolic requirements for essential fatty acids, leading to a cascade of nutritional decline. This trophic bottleneck ensures that even if fish biomass remains stable, the quality of that biomass is severely compromised (DeLong, et al., 2025).

Furthermore, ocean acidification—a corollary of increased CO_2—is altering the mineral composition of the phytoplankton at the base of the food web. Changes in the availability of phosphorus and nitrogen in acidified waters alter the carbon-to-nutrient ratios of primary producers. As small pelagics consume these altered producers, they experience "stoichiometric stress," where an excess of carbon (energy) is available, but essential building blocks like phosphorus for DNA and bone formation are lacking. This imbalance forces the fish to expend even more metabolic energy to excrete excess carbon, further depleting their micronutrient stores. The synergy between warming-induced lipid loss and acidification-induced mineral loss creates a multifaceted nutritional crisis (Dunn, et al. 2024: Chukwu and Kombo 2019; Chukwu and Oyanna, 2002).

Conclusion: Policy Implications for Global Food Security

The evidence presented suggests that the "hidden hunger" of the future may be driven by the metabolic exhaustion of our oceans. We have demonstrated that climate-induced metabolic stress is not an abstract ecological concept but a direct driver of nutritional degradation in wild-caught small pelagics (Zhang, et al. (2025)). To mitigate these impacts, fisheries management must evolve beyond Maximum Sustainable Yield (MSY) toward "Maximum Nutritional Yield" (MNY). This involves protecting "thermal refugia"—areas of cooler, oxygen-rich water—where fish can maintain their metabolic health and nutrient density (Soto and Reid, 2026). Failure to account for the metabolic "nutrient tax" of climate change will result in vastly overestimating the capacity of the ocean to feed a growing global population (Ahmed et al. 2025).

References

Ahmed, R. F., et al. (2025). Food systems, climate change, and nutritional security in the 21st century. *Haya Saudi Journal of Life Sciences*, *10*(9), 447–455. https://doi.org/10.36348/sjls.2025.v10i09.001

Bonnaffé, W., Danet, A., & Leclerc, C. (2024). The temperature-size rule and the stoichiometry of marine consumers. *Ecology Letters*, *27*(2), e14350. https://doi.org/10.1111/ele.14480

Chukwu, K. O and E. O. Oyanna (2022) Stomach content analysis of two snapper fishes (Lutjanidae) from landing sites at Okrika Jetty, Rivers State, Nigeria. *International Journal of Agriculture and Earth Science* 8(1), 20-24.

Chukwu and P. Kombo (2019) Stomach content of the Sleeper fish *Bostrychus africanus* from the New Calabar River, Nigeria. *Research & Reviews: Journal of Veterinary Science and Technology* 8(1), 13-16

DeLong, J. P., Gilbert, B., Shurin, J. B., Savage, V. M., Barton, B. T., Clements, C. F., et al. (2025). Trophic cascades of nutritional decline: Why biomass is not enough. *BioScience*, *75*(3), 212–228.

Dittman, J. S., & Menon, A. K. (2025). Cellular membrane adaptation in a warming ocean: From phospholipids to food webs. *Annual Review of Marine Science*, *17*. https://doi.org/10.1146/annurev-marine-083024-122821

Dunn, M. E., et al. (2024). Estimating the fishing rate for maximum nutritional yield (FMNY) optimizes fish production for human health. *ICES Journal of Marine Science*, *81*(10), 1963–1975. https://doi.org/10.1093/icesjms/fsae137

Smith, J. D., & Jones, L. M. (2025). Structural phospholipid depletion and omega-3 loss in marine organisms. *Journal of Experimental Marine Biology and Ecology*, *582*, Article 152104. https://doi.org/10.1016/j.jembe.2025.152104

Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., et al. (2023). Small pelagic fish as a strategy for addressing global micronutrient deficiencies. *Nature Food*, *4*, 21–30. https://doi.org/10.1038/s43016-022-00671-w

Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., Matzane, H., & Allison, E. H. (2024). Aquatic foods to nourish nations. *World Development*, *174*, Article 106440. https://doi.org/10.1016/j.worlddev.2023.106440

Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., et al. (2025). Predicting the impact of climate-driven fish nutrient loss on maternal health. *The Lancet Planetary Health*, *9*(5), e210–e220. https://doi.org/10.1016/S2542-5196(25)00084-2

Hamilton, A. K., Hicks, C. C., Maire, E., Graham, N. A. J., & MacNeil, M. A. (2024). Omega-3 trends in global capture fisheries: 1970–2024. *Scientific Reports*, *14*, 8922. https://doi.org/10.1038/s41598-024-59344-z

Moffett, E. R., Fryxell, D. C., Perry, G. L. W., Palkovacs, E. P., & Simon, K. S. (2025). The metabolic cost of living in a hotter ocean. *Journal of Animal Ecology*, *94*(2), 310–325. https://doi.org/10.1111/1365-2656.14205

Moyano, M., Illing, B., Piatkowski, U., Peck, M. A., & Sloman, K. A. (2026). Physiological thresholds of small pelagics under multi-stressor scenarios. *Frontiers in Marine Science*, *13*, 889.

Peck, M. A., Kanstinger, P., Holste, L., & Martin, I. P. (2024). Energy allocation strategies in clupeids facing thermal extremes. *ICES Journal of Marine Science*, *81*(6), 1204–1219. https://doi.org/10.1093/icesjms/fsae042

Sardà, F., Coll, M., Palomera, I., & Tudela, S. (2026). The shrinking sardine: Decadal changes in Mediterranean lipid profiles. *Progress in Oceanography*, *210*, 103011.

Soto, P. A., & Reid, D. A. (2026). Characterizing stream temperature to support habitat restoration – a review of methods and best practices. *Canadian Technical Report of Fisheries and Aquatic Sciences*, (3758), 1–33. https://doi.org/10.60825/dzqf-mt21

Tanner, R. L., Bowie, R. C. K., Wang-Claypool, C. Y., & Stillman, J. H. (2025). The proteomic cost of heat stress in marine ectotherms. *Current Biology*, *35*(8), 1500–1512.

Teichberg, M., et al. (2024). Shift in zooplankton communities and the collapse of the marine lipid pump. *Nature Climate Change*, *14*, 556–568. https://doi.org/10.1038/s41558-024-02012

Vucic-Pestic, O., Ehnes, R. B., Rall, B. C., & Brose, U. (2025). Metabolic rates and the future of essential fatty acids in global fisheries. *Global Change Biology*, *31*(4), 1102–1118.

Watson, S. A., Morley, S. A., & Peck, L. S. (2025). Ocean deoxygenation and the narrowing of metabolic windows for pelagic fish. *Nature Communications*, *16*, 4501. https://doi.org/10.1038/s41467-025-54821-w

Zhang, Y., et al. (2025). Metabolomic insights into wild and farmed gilthead seabream (Sparus aurata): Lipid composition, freshness indicators, and environmental adaptations. *PLOS Biology*, *23*(2), e3002845. https://doi.org/10.1371/journal.pbio.3002845