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Amazon river plume: Where microalgae go carnivorous to win

In the vast plume of the Amazon River, microscopic algae adopt a surprisingly flexible survival strategy: They combine photosynthesis with the uptake of organic matter. An international research team led by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) has now shown that this so-called mixotrophy becomes the dominant and most successful lifestyle in mature plume waters. The findings, which are now published in Nature's journal "Communications Biology", reveal a previously underappreciated mechanism shaping marine food webs and carbon cycling in one of the ocean's largest river-influenced systems.

The Amazon River discharges enormous volumes of freshwater into the tropical Atlantic – accounting for around 50 % of all freshwater input into this ocean region and up to 20 % globally. This freshwater forms a huge plume that spreads over hundreds of kilometres and evolves over distance and time, creating a mosaic of habitats with distinct physical and chemical conditions. Within this dynamic environment, microscopic organisms inhabit the water column and form the base of the region's extensive marine food web – collectively referred to as plankton. Traditionally, plankton has been divided into plant-like phytoplankton (or microalgae), which perform photosynthesis, and animal-like zooplankton, which feed on other organisms. However, growing evidence shows that many microalgae do not fit neatly into this scheme. Instead, they combine photosynthesis with the uptake of organic matter and even feeding on other microscopic living beings, thus blurring the classical boundary between producers and consumers. The new study now provides compelling field-based evidence that this hybrid strategy – mixotrophy – is not just a curiosity but an important ecological mechanism.

Tracing hidden nutritional strategies in plankton communities

Recognising different nutritional strategies within mixed plankton communities has long been a major challenge in marine ecology. A key innovation in this field is the use of amino acid nitrogen stable isotope analysis of plankton samples filtered from the water column. Depending on which nutritional strategy dominates, characteristic isotope patterns can be detected and used to infer the trophic position of plankton organisms within the food web.

In the study now presented in Nature's journal *Communications Biology*, the researchers combined this isotope-based approach with complementary analyses of environmental conditions and plankton community structure, including pigment-based and microscopic observations. This integrated framework allowed them to identify and characterise mixotrophic activity directly within a highly dynamic natural system, rather than under controlled laboratory conditions.

"By integrating amino acid nitrogen stable isotope analyses with environmental and community data, we can now identify mixotrophic activity directly in natural systems – something that was previously very difficult to achieve under field conditions," says Ana Fernández-Carrera from the Institute of Oceanography and Global Change at the Spanish Universidad de Las Palmas de Gran Canaria. She is the study's lead author and took part in the second of the two IOW-joined and led research cruises in 2018 and 2021 to investigate planktonic food web patterns in the Amazon River plume. Being an IOW scientist at the time, she analysed a total of 46 plankton samples from 29 stations across the plume. In addition, the expedition teams measured key environmental parameters such as nutrient concentrations, phytoplankton pigments, oxygen content, and water column structure to characterise changes in physicochemical conditions along the aging plume.

In dynamic conditions mixotrophy pays off

Along the aging gradient of the Amazon plume, Fernández-Carrera and her research team identified a clear pattern in trophic strategies. In younger waters closer to the river mouth, trophic position values clustered around 1.0, indicating a dominance of purely photosynthetic organisms. As the plume matures – after approximately 27 days – these values shift towards about 1.5, reflecting an increasing contribution of mixotrophic nutrition in these older, so-called "Outer Plume Margin" waters, while still remaining below values around 2.0 that would indicate predominantly heterotrophic feeding.

This transition is linked to pronounced changes in environmental conditions along the plume. As the water ages, nutrient concentrations decline; nitrate, for instance, drops from elevated levels in the young plume to around 2 µM on the continental shelf, before decreasing even further offshore. At the same time, chlorophyll concentrations decrease from above 0.5 µg L^{-1} in fresher waters to about 0.17 µg L^{-1} and the water column becomes less stratified with increasingly thick mixed layers (> 20 m) relative to the young plume; oxygen conditions shift towards slightly undersaturated surface waters.

Under these increasingly nutrient-limited and physically heterogeneous conditions – shaped by the interplay of the thickness of the upper mixed layer, oxygen availability, and biological production – organisms that combine photosynthesis with the uptake of dissolved organic matter or prey outcompete both, strictly autotrophic and strictly heterotrophic organisms. "This clear pattern shows that mixotrophy is not an exception but can be a dominant and highly efficient strategy under certain environmental conditions," explains corresponding author Natalie Loick-Wilde, senior scientist on both expeditions and long-standing expert in marine plankton food web ecology at the IOW.

Why mixotrophy matters for climate research and ecosystem management

The implications of these findings extend far beyond the Amazon region, as they challenge the traditional view of marine food webs as being structured by a simple division between producers and consumers. Instead, they reveal a continuum of nutritional strategies, with mixotrophy playing a central role. "Mixotrophy is widespread and functionally important – it cannot be ignored and should be adequately represented in models so that we can gain a more realistic picture of how marine ecosystems function," Ana Fernández-Carrera emphasises.

In addition, the study suggests that mixotrophs play a key role in the ocean's carbon cycle. In the Amazon's outer plume margin, where mixotrophy dominates, previous research has identified a significant sink for atmospheric carbon dioxide. "Mixotrophic activity might enhance the production and accumulation of carbon-rich but inedible and thus refractory organic matter, thereby contributing to long-term carbon storage in the ocean driven by the microbial carbon pump," Natalie Loick-Wilde explains.

Both scientists agree that identifying why, when and where mixotrophy becomes dominant, is key to understanding marine regions, where essential ecosystem processes are particularly active. Such areas may play a disproportionate role in carbon cycling, nutrient dynamics, and energy transfer within marine food webs. "Improving our understanding of these patterns can help refine ocean and climate models and support more effective ecosystem management, including the protection of biologically productive regions important for fisheries and biodiversity. To achieve this, future research especially needs to further refine analytical methods to better resolve isotopic signatures of mixotrophic plankton and to extend such observations to other regions of the global ocean", the two planktologists conclude.

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