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Decoding the Biological Pump: Isotopic Insights into Nutrient Sequestration Across the Past, Present, and Future Ocean

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The marine nitrogen and carbon cycles are fundamentally coupled through the biological pump, which transfers ~5-12 Pg of carbon annually from the surface to deep ocean, helping regulate global climate. However, our understanding of the complex processes that drive export flux and their response to ocean warming remain poorly constrained. The biological pump redistributes bioavailable nitrogen and carbon largely in the form of amino acids in phytoplankton aggregates and zooplankton fecal pellets. Amino acids are typically viewed through the lens of their inherent lability, where diagenetic alteration and selective preservation erase or overprint primary geochemical signals. Here, we show that compound specific nitrogen isotopes of amino acids ($d^{15}N_{AA}$) in marine sediments are instead remarkably well preserved across a globally representative range of depositional settings, ages and degradation states. We present a conceptual framework to reconcile the selective preservation of amino acid molar abundances with the apparent non-selective preservation of $d^{15}N_{AA}$. We then demonstrate the use of isotope mixing models based on $d^{15}N_{AA}$ signatures of phytoplankton, heterotrophic bacteria, and fecal pellets to quantify proportional contributions of these endmember sources to sediments over space and time. Our analysis reveals a depth-dependent transition in the origin of amino acids, from mostly phytoplankton in shallower waters to mostly fecal pellets in deeper waters. The ability to reconstruct the relative importance of these delivery mechanisms may present new opportunities for predicting the ocean's capacity for carbon and nitrogen sequestration in a warming world.