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Phosphorus cycle in focus

Ecosystems have long been shaped by phosphorus limitation. We need to better understand how natural and human-caused shifts in the phosphorus cycle disrupt the Earth system.

Algal bloom caused by phosphorus from agricultural runoff.

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Life would be impossible without phosphorus. Present in molecules from DNA to membrane lipids to the compounds that shuttle energy in cells, it acts as an essential nutrient alongside nitrogen. Phosphorus moves through the environment in vigorous biogeochemical cycles, reflecting its chemical reactivity and intense competition by hungry organisms. In this issue, accompanied by an online focus of research from the *Nature Geoscience* archive, we explore how phosphorus has helped to set the pace of ecological and geochemical processes throughout Earth history.

Phosphorus limitation set the early Earth's biological and climatic trajectory. In a Review in this issue, Hao et al. review constraints on phosphorus availability during Earth's first two billion years, proposing that abiotic weathering reactions led to the buildup of a large pool of bioavailable phosphorus that could have supported the earliest life. The emergence of a biosphere reliant on the element subsequently encouraged the evolution of strategies suited to cope with phosphorus scarcity, though phosphorus has remained a key nutrient ever since. The subsequent rise of atmospheric oxygen around 2.4 billion years ago was enabled by an invigoration of continental weathering that led to more sediment-bound phosphorus becoming available to oxygen-producing phytoplankton[1].

Today, phosphorus in seawater controls the productivity of phytoplankton forming the base of marine food webs[2,3]. Surface ocean phosphorus concentrations are generally low due to high demand, with the exception of upwelling zones of nutrient-rich deep waters where supply can outstrip demand. Not only must phosphorus be present, it also needs to be bioavailable, as discussed by Shlomit Sharoni in a Q&A in this issue. Inorganic phosphate is easily incorporated by most organisms, but much marine phosphorus is locked up in complex organic matter dissolved in seawater, typically accessed only by microbes adapted to nutrient-stressed conditions.

Phosphorus limitation extends to the land as well. It has been estimated that 43% of the Earth's land area is primarily phosphorus limited, with another 39% being co-limited alongside nitrogen[4]. Tropical soils have especially low levels of phosphorus despite verdant overlying forests, a consequence of intense water cycling stripping nutrients from soils. Although enhanced $p\text{CO}_2$ levels can spur plant growth in forests, any increased carbon sequestration capacity may be constrained by phosphorus scarcity[5,6]. Limitation can be overcome in unexpected ways, such as the fertilization of the Amazon by of phosphorus-rich dust blown from the Sahara as Kelly Andersen points out in this issue's Q&A.

The modern phosphorus cycle has been profoundly meddled with by humans to overcome phosphorus limitation. Half of the phosphorus available to crops in agricultural soils may come from fertilizer application[5]. Fertilizer is a limited resource – often derived from ancient rocks composed of detritus deposited beneath marine upwelling zones – and its depletion will eventually lead to problems for agriculture and other organisms that rely upon it.

This anthropogenic phosphorus also tends not to stay put, but readily runs off from soils. When freshwater lakes and streams receive a spike of phosphorus from such agricultural runoff, the decomposition of the resulting algal blooms can crash dissolved oxygen relied upon by fish and other animals with disastrous consequences for lake ecosystems. This process can be seen in the unprecedent accumulation of phosphorus in lakes around the world[7].

There are lessons from the past on the consequences of disruptions to the global phosphorus cycle. The end-Permian (~252 million years ago) and Late Ordovician (459–444 million years ago) mass extinctions have been linked to high primary productivity and anoxia caused by a relatively fast buildup of phosphorus in the ocean[8,9]. Large volcanic eruptions preceded both events, and the intense weathering of recently formed igneous rocks on land was the likely cause of the nutrient spike.

Depleted since the establishment of life on Earth, human activities have led to localized overabundances of phosphorus, with wide-ranging biogeochemical implications. Understanding how phosphorus cycling changes in the midst of wider global environmental changes is required to protect the functioning of our future Earth.

References

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