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# Investigating the long-term impact of nutrient supply on global oceanic primary production.

**DAVID STAPPARD**[1], JAMIE WILSON[2], ANDREW YOOL[3] AND TOBY TYRRELL[1]

[1]University of Southampton
[2]University of Liverpool
[3]National Oceanography Centre

In Earth's past, present and future, oceanic primary production forms the foundation of marine food webs, contributing to the global carbon cycle and atmospheric gas composition. Bottom-up controls on oceanic primary production include light, temperature, and nutrient supply, of which nutrient supply is the most dynamic. A large number of measurements and experiments have led to identification of the immediately most limiting nutrient for oceanic primary production, specifically the proximate limiting nutrient (PLN). However, less progress has been made on understanding the long-term (multi-millennial) dynamics of nutrient limitation, that is, identification of the ultimate limiting nutrient (ULN; the nutrient whose supply controls system productivity over extensive timescales), which can differ from the PLN. We present findings from the carbon-centric Grid Enabled Integrated Earth system model (cGEnIE), modified to include the nutrients phosphate, nitrate, and iron simultaneously. Whereas previous modelling studies have only included nitrate and phosphate, this new model also includes iron, providing new insights into how nutrient supply influences long-term levels of oceanic primary production. Our work indicates that the dynamics of the oceanic iron cycle set an upper bound to the levels of oceanic primary production. Therefore, oceanic primary production has most likely not greatly exceeded the modern rate ever since oceanic oxygen concentrations increased to modern levels. This new understanding suggests, however, a potential tipping point when ocean oxygen concentrations fall (for instance during oceanic anoxic events) when iron should become more soluble in seawater, leading to greater inventories of bioavailable iron and removing the iron-imposed upper limit on oceanic primary production. This new study gives insight into how temporally varying nutrient inputs can affect oceanic primary production, and therefore the role of the ocean in Earth's past atmospheric composition and carbon cycles, as well as its potential future influence.