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Introduction to the Biogeochemical Flows Boundary

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Earth's elements flow. Carbon, nitrogen, calcium, and phosphate (among many others) cycle through the biosphere, oceans, lakes, rivers, the atmosphere, rocks, and soils at regional and global scales (see Berner & Berner 2012). In the planetary boundaries framework two elements are the focus: phosphorus and nitrogen. Both are key constituents for life, and both have been significantly impacted by anthropogenic forces, especially the production of food through industrial agriculture. The flows of other elements matter, too. The flow of carbon, for instance, is implicit in the climate change boundary and for biosphere integrity. Yet phosphorus and nitrogen hold a special place owing to the ways their limits and excesses affect terrestrial and aquatic ecosystems. In the planetary boundaries framework, they are measured slightly differently. Phosphorus is assessed both globally and regionally, while nitrogen is treated only at the global scale – although there are proposals to measure nitrogen regionally too (see Schulte-Uebbing et al. 2022). It should be noted, too, that initially phosphorus was only treated globally, through focus on the ocean. After interventions by freshwater ecologists, however, phosphorus was subsequently treated regionally and in terms of freshwater impacts (see Carpenter & Bennett 2011). Each of phosphorus and nitrogen are measured in terms of their sustained flows from rivers to the ocean and measured in Teragrams (1 Teragram = 1 billion kilograms). For phosphorus, the boundary is 11Tg, and for nitrogen the boundary is 6.2Tg (Steffen et al. 2015).

Nitrogen and phosphorus flows differ in important ways for understanding how respective human uses affect people, other species, and ecosystems. Perhaps most salient is that while nitrogen is naturally occurring it can also be synthetically produced for application as a dry fertilizer or as anhydrous ammonia (NH_3), a form of liquid nitrogen applied to soils where it bonds to subsurface moisture. The invention of synthetically produced nitrogen in the twentieth century led to large increases in its use, and to significant pollution owing to runoff from agricultural land as the result of excess application. Phosphorus, by contrast, cannot be

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synthetically produced at industrial scales. It is primarily mined from existing deposits, and this has been a driving feature of both its exploitation in colonial and post-colonial contexts as well as in contemporary agricultural economies that are increasingly globalized. This presents additional challenges regarding how it is sourced, from where, and the politics of controlling an element that is vital to the global food supply (Cordell & White 2014; Elser & Haygarth 2021).

Nitrogen and phosphorus also have shared features. Excessive release of either into freshwater systems can lead to the eutrophication of lakes. It can also lead to 'dead zones' where rivers meet the sea, such as the Mississippi in the Gulf of Mexico, where the cumulative impact of the fertilizer choices of many farmers affect aquatic ecology and the livelihoods that depend on healthy oceans. Histories of nitrogen and phosphorus use also generate significant inequalities when the planetary boundaries framework is used to determine 'fair shares' for using them in the future or for ecosystem recovery from past uses (Sandström et al. 2023).

Outside of the planetary boundaries framework there are also significant ethical issues to consider, as the two chapters in this section also show in their own ways. These require situating the insights of the planetary boundaries framework in larger considerations of history, colonialism, ecosystem science, and environmental governance.

Teaiwa argues that the phosphorus mining critical to food security must be placed amid histories of colonialism and ongoing forms of extraction. Teaiwa seeks to trouble narratives – disciplines, even – that do not grapple with how gendered forms of dispossession affected leadership and governance by Indigenous women while introducing separations of people from land in the name of putting phosphorus in service to a larger humankind. By contrast, Elser examines phosphorus through two perspectives: one that prioritizes technological innovation and one concerned with environmental degradation. Offering an overview of the debate between these positions from the Green Revolution to today, he outlines how elements of both must be combined in a new kind of 'systems innovation' in order for sustainable phosphorus use to be achieved.

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