POLLUTION

The global nitrogen-phosphorus imbalance

The imbalance has grave consequences for natural ecosystems and global food security

By **Josep Peñuelas**[1,2] and **Jordi Sardans**[1,2]

Exponential increases in the human population and its activities are accelerating global changes, from the climate to land use to loss of species. The rise in atmospheric concentrations of greenhouse gasses, mainly CO_2 from the combustion of fossil fuels, is the most well-known driver of global change (*1*). Emission of greenhouse gases, which also include methane (CH_4) and nitrous oxide (N_2O), are stoking global warming as well as more frequent and extreme weather events, such as droughts and floods. Land use and pollution also have major impacts on Earth's future (*1*). Among these ongoing anthropogenic changes, the biospheric nutrient imbalance between nitrogen (N) and phosphorus (P) is less known and deserves more attention.

In 2003, a pioneering study by Sterner and Elser reported that the aquatic N/P ratio determined the community structure and function of plankton in lakes (*2*). When the concentrations of both N and P are not limited, the rate of protein synthesis by plankton depends mostly on the amount of P-rich RNA that the organisms produce and is therefore negatively correlated with the cellular N/P ratio. Thus, lower N/P ratios are associated with faster protein synthesis and higher growth rates of plankton (*2*). This negative correlation has multiple ecological consequences for the structure and functioning of ecosystems, as has been reported in all types of ecosystems.

Human activities have substantially altered this N/P ratio in water, soils, and organisms over the past five decades (*3*). The much faster increase of anthropogenic inputs of reactive N to the biosphere than inputs of P has led to a global increase in the N/P ratio. The main anthropogenic sources of reactive N include the many kinds of nitrogen oxides from burning fossil fuels, the planting of N-fixing crops, and the use of N-rich fertilizers as well as their runoff into waterways. Although there are also human activities that have increased the amount of P in soils and waters—for example, from the application of P-rich fertilizers and detergents—the overall increase in the input of P is dwarfed by that of N. This increase in both N and P has led to eutrophication (excess of nutrients) of waters and soil. Some countries have implemented water-treatment strategies to decrease N and P concentrations. However, the technology used by these water-treatment plants retains more P than N and therfore increases the N/P ratio as an unintended consequence (*4*). The global N/P ratio of anthropogenic inputs has increased from about 19:1 in molar basis in the 1980s to 30:1 in 2020 (*3*). The interactions of these N/P ratios in water, soil, and organisms with drivers of global change, such as warming and increasing atmospheric CO_2 concentrations, further increase the N/P ratio in some biomes (*5*).

The current global N/P ratio of anthropogenic inputs is thus larger than the averages of the main ecosystem compartments such as soil (up to 22:1), humus (up to 17:1), ocean water (up to 16:1), terrestrial plants (up to 30:1), and plankton (up to 16:1). This imbalance at the global scale may be even greater at the local-regional scale because the inputs of N and P are not evenly spread around the world, and because N and P have very different mobilities in the environment. P tends to have low water solubility and volatilization, is often adsorbed and precipitates in soil as salt minerals, and is buried in sediments, thus tending to remain near the emission sources. By contrast, N is much more water-soluble and volatile and thus tends to spread out over a larger radius from its sources (*3*).

The biological impacts of the increasing N/P imbalance have already been observed and reported in the trophic communities of several continental water bodies (*6*), in the structure and function of soil communities (*7*), and in the species composition of plant

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The use of nitrogen-rich fertilizers and their runoff into waterways are major contributors to the growing imbalance of nitrogen and phosphorus.

communities (*8*). The impact of the imbalance will continue to increase as the imbalance continues to tip in the same direction.

This increasing N/P imbalance can have severe consequences not only for natural ecosystems but also for human societies because crop production and food security will be affected. The resource gap in remedying this imbalance at the regional level may also broaden the economic gap between rich and poor countries (*9*). N-containing fertilizers have an unlimited source—the atmosphere—from which N can be extracted through the Haber-Bösh reaction. This innovation has allowed a continuous increase in the production and use of these N fertilizers since the 1950s (*10*). By comparison, P sources have largely been limited to mines and are concentrated in very few countries, such as Morocco (*9*), so P might eventually become economically inaccessible to low-income and food-deficient countries as these sources become depleted. In the future, P-producing nations are likely to manage their reserves to maximize profit for both their domestic mining and farming industries, making P-based fertilizers increasingly unaffordable for farmers in the poorest countries (*9*) and worsening the N/P imbalance in regions where the problem is the most prominent.

Imbalanced soil N/P ratios can also affect the chemical composition of crops, which can have implications on public health. For example, in some regions P accumulates in soils and water bodies, and the N/P ratio decreases, as a result of an excessive use of inorganic and organic P fertilizers (*3*). Food produced in these environments may lead to an overconsumption of P in the local population, which can have negative implications for their health (*11*). The implications of this global imbalance between N and P could also have impacts on several other human infectious and noninfectious illnesses that are strongly associated with diet, such as coeliac disease (*12*).

Besides the imbalance observed in the N/P ratio, human activities also generate imbalances among other elements. For example, changes in the ratio of carbon (C) and N relative to iron, zinc, calcium, and potassium, among others, have been observed in plant tissues (*12*). The increasing atmospheric concentrations of CO_2 are likely a driver of the increase of C in plants, which in turn have developed more compounds that reduce the concentrations of these other elements (*12*). This indirectly leads to the displacement of the elemental composition (elementome) (*13*) of organisms, communities, and entire ecosystems owing to imbalances of the anthropogenic biospheric inputs of C and N relative to P and other elements in recent decades and is likely to exacerbate in the coming decades.

The time has come for national and international environmental agencies and policy-makers to recognize the risks of unbalanced N/P ratios and other parallel imbalances in elemental stoichiometry to the biosphere and humanity. The international environmental agencies and policy-makers should address the problem through a coordinated international policy. Observations, experimentation, theory, and modeling at different temporal and spatial scales are warranted to evaluate, predict, and provide possible solutions to these anthropogenic nutritional imbalances and their effects on nature and humans. Among these possible solutions, increasing the efficiency of use and cycling of N and P—for example, through precision agriculture to avoid misuse of fertilizers, methods to increase plant accessibility to P sources, use of innovative management techniques and biotechnologies to improve nutrient-use efficiency, stimuli and subsidies for recycling P through legislative regulations and instruments at the national or regional administrative level, or reduction of livestock production—has been suggested as the most effective approach to prevent imbalanced N/P ratios for food production and reduce environmental problems that involve N and P. This research will determine whether these nutritional imbalances should be added to the planetary boundaries instead of only considering N and P separately (*14*). ■

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VIEWPOINT: COVID-19

Nervous system consequences of COVID-19

Neurological symptoms highlight the need to understand pathophysiologic mechanisms

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Although severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is considered a respiratory pathogen, myriad neurologic complications—including confusion, stroke, and neuromuscular disorders—manifest during acute COVID-19. Furthermore, maladies such as impaired concentration, headache, sensory disturbances, depression, and even psychosis may persist for months after infection, as part of a constellation of symptoms now called Long Covid. Even young people with mild initial disease can develop acute COVID-19 and Long Covid neuropsychiatric syndromes. The pathophysiological mechanisms are not well understood, although evidence primarily implicates immune dysfunction, including nonspecific neuroinflammation and antineural autoimmune dysregulation. It is uncertain whether unforeseen neurological consequences may develop years after initial infection. With millions of individuals affected, nervous system complications pose public health challenges for rehabilitation and recovery and for disruptions in the workforce due to loss of functional capacity. There is an urgent need to understand the pathophysiology of these disorders and develop disease-modifying therapies.

Initial reports of neurologic syndromes accompanying COVID-19 described changes in level of consciousness or cognitive dysfunction, weakness, and headache in hospitalized patients that might be attributable to any severe acute illness with respiratory and metabolic disturbances. Subsequently, reports of strokes and acute inflammation

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