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The co-evolution of life and biogeochemical cycles in our planet

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Abstract: The Earth has undergone numerous geological and biological changes over billions of years. The evolution of plants and animals had a direct relationship with the elements' changes in the atmosphere and the development of the biogeochemical cycles on Earth. The Anthropocene is the age of the *Homo sapiens* leaves its geological signature on the planet. Human domination and/or interference in the biogeochemical cycles results in an environmental change that affects not only ecosystems, in general, but also the biota and global biodiversity. In this way, we are creating another mass extinction event, the "sixth extinction wave" as well as transforming the ecosystems' functions and services.
Keywords: *carbon; oxygen; nitrogen; biota.*

A coevolução da vida e os ciclos biogeoquímicos em nosso planeta

Resumo: A Terra passou por inúmeras mudanças geológicas e biológicas ao longo de bilhões de anos. A evolução de plantas e animais teve uma relação direta com as mudanças dos elementos na atmosfera e o desenvolvimento dos ciclos biogeoquímicos na Terra. O Antropoceno é a idade em que a espécie *Homo sapiens* deixa sua assinatura geológica no planeta. A dominação e/ou interferência humana nos ciclos biogeoquímicos resulta em mudanças ambientais que afetam não apenas os ecossistemas, em geral, mas também a biota e a biodiversidade global. Dessa forma, estamos criando um novo evento de extinção em massa, a "sexta onda de extinção" ("the sixth extinction wave"), além de transformar as funções e os serviços ambientais dos ecossistemas.
Palavras-chave: *carbono; oxigênio; nitrogênio; biota.*

Introduction

Before life emerged on Earth, there were only geochemical cycles defined as the movement of elements between major Earth reservoirs, mediated by rock weathering, erosion, volcanism, and subsidence among others. Organisms obtain energy by reducing CO_2 using a series of electrons donors through oxi-reduction reactions involving a series of major elements, like carbon, nitrogen, phosphorus and sulfur. In this process, the organisms promote the cycling of major elements coupled with major tectonic events mentioned above, characterizing the major BIO-GEO-chemical cycles of the planet (Falkowski 2011).

In the quest for energy by organisms, there an intrinsic link between biodiversity and the chemical processing of major elements was permanently established. This link started with the first unicellular chemoautotrophic organism on the planet that probably was formed more than 3 billion years ago (Nutman et al. 2016) and obtained energy by reducing CO_2 with H_2, generating an organic molecule (acetate) and water. The formed acetate was further oxidized to methane and CO_2 generating energy in a metabolic process known as Wood–Ljungdahl pathway (Weiss et al. 2016).

Life on the planet only became more complex when cyanobacteria started to harvest sunlight to reduce CO_2, using oxygen as the final electron acceptor. The beginning of photosynthesis started to oxidize the atmosphere with profound effects not only in the biogeochemical cycles but also on the distribution of strictly anaerobic organisms, leading several species to extinction. The increase of oxygen in the atmosphere (The Great Oxygenation) also caused changes in the geological cycle of several elements, through the oxidation of several minerals. For instance, pyrite (FeS_2) was oxidized to $Fe(OH)^-$ and formed sulfuric acid, leading to more weathering. Free iron (Fe^{+2}) was also oxidized to Fe_2O_3, and this oxidation process was beautifully marked in red in rocks such as the Itabirito present mainly in the Minas Gerais State.

Before harvesting the sun through photosynthesis, complex life on the planet was constrained by a lack of energy, allowing only the existence of unicellular aquatic organisms. Photosynthesis by cyanobacteria started a new era of life diversity on the planet. Before that, the rising of cyanobacteria sucked up a lot of CO_2 from the atmosphere, decreasing the greenhouse effect leading to cooling, and eventually an extensive snow cover of the planet called Huranian snowball, again with profound consequences for the living biota. A series of volcanic eruptions in the ocean floor injected back enormous amounts of CO_2 into the atmosphere warming the planet again, melting the snow cover, and allowing the flourishing of life again. The atmospheric O_2 concentration was not at that time as high as today but start to increase as the more produced organic matter was progressively buried in sediments, avoiding the consumption of atmospheric O_2 in the decomposition process. At the end of the Proterozoic, a new oxygenation period (Neoproterozoic Oxygenation) occurred bringing the atmospheric oxygen concentration to levels like today's concentration. Finally, there was enough energy available on Earth to create more complex organisms. However, before this happened, the Earth experienced two more snowballs, not as extensive in space and time as the Huranian snowball, but enough to again to change the species distribution on the planet. With the end of snowballs, the Earth experienced a dramatic change in the diversity and complexity of organisms (Payne et al. 2011). However, this was not a smooth ride from there to our days. The Earth face five massive extinctions in the last 0.5 billion years, and there are pieces of evidence that we are facing the sixth extinction. These extinctions are important because although several species have vanished from Earth, a novel set of animals and plants surged by the opening of new ecological opportunities. Four out of six extinctions were caused by an imbalance of the major biogeochemical cycles, especially of the carbon and oxygen cycles that will briefly be described below.

Planetary Links between Life and Biogeochemical Cycles

1. The carbon cycle

The carbon cycle may be divided into main parts, one long cycle denominated the geological carbon cycle, and the other called the biological carbon cycle that is relatively much shorter than the geological cycle. Rock weathering and volcanism are the two main processes that regulates the geological cycle. Weathering is the chemical process where primary minerals are transformed into secondary minerals in a reaction where CO_2 is consumed and transformed into HCO_3^-, which is transported to the ocean via rivers. In the ocean, the bicarbonate is chemically or biologically transformed into calcite (calcium carbonate), which is resistant to decomposition and sinks to the bottom of the ocean. From there, calcium carbonate is transferred to the interior of the Earth by the subsidence process. Under high temperature and pressure in the Earth's interior, calcium carbonate reacts with SiO_2 forming a new primary mineral. In this reaction, CO_2 is produced, turning back into the atmosphere by volcanic activity, closing the geological carbon cycle. The balance between weathering and volcanism could be summarized by the following reaction (Equation 1):

$$CaSiO_3 + CO_2 \underset{\text{metamorphism}}{\overset{\text{chemical weathering}}{\rightleftarrows}} CaCO_3 + SiO_2$$

Equation 1: Reaction summarizes the balance between chemical weathering and volcanism during the geological carbon cycle.

The chemical weathering proceeds in the soil pore, where soil water reacts with CO_2, mainly produced by soil respiration, and formed carbonic acid, a weak acid that reacts with minerals, releasing basic cations depending on the mineral. The following reaction (Equation 2) illustrates the weathering of a calcium silicate:

$$2CO_2 + H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO^-_3 + SiO_2$$

Equation 2: Equation illustrates carbonic acid reacting with calcium silicate during the chemical weathering in the soil pore.

In the ocean, the bicarbonate combines with Ca to form calcium carbonate, a major constituent of the shells of several organisms in the ocean. After the death of these organisms, calcium bicarbonate precipitates into the ocean floor (Equation 3).

$$Ca + 2HCO_3 \rightarrow CaCO_3 + H_2O + CO_2$$

Equation 3: Reaction illustrates the combination between bicarbonate and calcium in oceans.

It is important to note that of the two atoms of carbon in the bicarbonate, one goes to the formation of calcium carbonate and the other is transformed into dissolved CO_2. This dissolved CO_2 is fuel for the photosynthesis of many organisms in the ocean, linking the geological and the biological cycle of carbon. This last sequence illustrates the coupling of the geological and the biological carbon cycle, which is regulated by two main processes, photosynthesis, and respiration. Photosynthesis is chemically a reduction CO_2 reaction, forming a carbohydrate and liberating oxygen, the final electron acceptor. Once the carbohydrate is formed, it can be respired (oxidized), generating energy for the organism and producing CO_2 and water.

The atmospheric CO_2 concentration is ultimately controlled by the ocean, which has 50 times more CO_2 than the atmosphere. The CO_2 diffuses from the atmosphere into the ocean against a gradient of concentrations, two mechanisms are necessary: the solubility and the biological pumps. The first CO_2 dissolves more in cold water, at higher latitudes, became denser and sinks transferring CO_2-rich water from the surface to the bottom. In the biological pump, the second mechanism, dissolved CO_2 on the surface is taken up by photosynthesis, the most part returns by oxidation of this organic material in the water column, but a minor part reaches the bottom. The other mechanism is the biomineralization described above, where calcium carbonate shells sink to the bottom carrying CO_2 from the surface to the bottom against a CO_2 concentration gradient.

The biological part of the carbon cycle was already mentioned above, but it is worth repeating that this part of the cycle is controlled by photosynthesis and respiration through the Equation 4:

$$CO_2 + H_2O \leftrightarrow (CH_2O)_n + O_2$$

Equation 4: Reaction summarizes the photosynthesis and respiration processes during the biological carbon cycle.

These equations are entirely mediated by organisms and define the productivity of an ecosystem. The Gross Primary Productivity (GPP) is defined as the total amount of organic matter produced by photosynthesis, and the Net Primary Productivity (NPP) is the GPP minus the amount of organic matter that is oxidized. If the NPP is positive, the ecosystem is increasing its biomass, if the NPP is negative, the ecosystem is losing organic matter.

2. The oxygen cycles

One of the main features of our plane is to maintain a relatively constant concentration of free molecular oxygen in the atmosphere (O_2). The concentration of this gas in the atmosphere is a result of interaction between biological and geochemical processes (Petsch 2014). The main source of oxygen to the atmosphere is the photosynthesis process initiated approximately 2.4 billion years by the cyanobacteria. In simple terms, photosynthesis is the transformation of the radiant energy of the Sun into chemical energy captured in a carbohydrate molecule, such as glucose. In other words, is the reduction of the atmospheric CO_2, where the splitting of the water molecule provides the hydrogen, and O_2 is the final acceptor of electrons (Falkowski et al. 2011). Photosynthesis is made by autotrophs organisms, including, plants, algae, and cyanobacteria. These are the primary producers that are the base of the food chain. Approximately half of the carbon fixed by photosynthesis is in the ocean, by phytoplankton and cyanobacteria. On land, most of the photosynthesis takes place in tropical areas due to high temperatures and rainfall, which in part explains the high plant biomass in this region of the globe.

On the other hand, oxygen is consumed in two main processes, the oxidation of some minerals, and mainly via oxidation of the organic matter promoted by autotrophs (plants) and heterotrophs (animals) in search of energy. Plant respiration is used to maintain and produce biomass. Soil respiration includes the autotrophs respiration by microorganisms, like plants, but mainly the breakdown of dead organic material by heterotrophs. Oxygen is consumed in this process as above mentioned, but CO_2 is released back into the atmosphere. During the Carboniferous Period, organic matter was not oxidized in the same proportion of its production. Consequently, extensive formation of coal and oil occurred during this Period, which is returning to the atmosphere via fossil fuel combustion, increasing atmospheric CO_2 concentration and causing global warming.

The oxidation of minerals occurred when reduced minerals are exposed to O_2 via uplift or erosion of the Earth's surface. The oxidation of Fe^{+2} to Fe^{+3} is one of the most common oxidations of Fe-bearing minerals. The presence of banded iron formations (BIF) by the Fe^{+2} oxidation was one of the first pieces of evidence that the atmospheric O_2 concentration was increasing due to the cyanobacteria photosynthesis.

Secondarily, O_2 can be consumed by the oxidation of volcanic gases in the atmosphere, by chemolithotrophic organisms that oxidized inorganic compounds instead of organic compounds to produce energy, and by photooxidation, where organisms are not involved (Petsch 2014).

As part of the organic matter produced is buried in sediments, there is a 21% excess of oxygen in the atmosphere, evidencing that the oxygen cycle is not in equilibrium (Falkowski et al. 2011).

3. *The nitrogen cycle*

The nitrogen cycle can be viewed as a sequence of oxi-reduction reactions mediated by microorganisms in search of energy. Approximately 78% of the atmosphere is composed of N_2, two molecules of nitrogen strongly bounded, which make this an inert compound, useless for most organisms. At the same time, nitrogen, like phosphorus, is one of the most limiting nutrients in terrestrial and aquatic ecosystems. N_2 only becomes available to organisms through the nitrogen biological fixation (NBF) when bacteria of the genus *Rhizobium*, living in symbioses with species of the superfamily Fabaceae, convert N_2 to a reactive form of nitrogen (NH_3). In the plant, nitrogen is incorporated into several tissues as organic-N, and after death and the initiation of the decomposition process, organic-N is reduced to NH_4 by soil microorganisms in a process called mineralization. NH_4 can be taken up by plants or oxidized to NO_3 by another group of soil microorganisms. Nitrate can be taken up by plants, leached out of the soil profile, or reduced to N_2 or N_2O, which are gaseous form that diffuse from the soil to the atmosphere.

4. *Great flowering and extinctions of life on earth and biogeochemical cycles*

Paradoxically, the first large extinction on Earth was preceded by an increase in large size and architectural complexity of species that started in the Eon Neoproterozoic, the so-called Ediacaran biota, probably caused by post-glacial oxygenation of the Earth as explained above (Narbonne 2005). Although there was not yet mobility among animal taxa of the Ediacaran, Narbonne (2005) advocates that the communities present at that time were diverse enough to a point to resemble modern marine ecosystems. However, such biodiversity did not preclude the disappearance of most of these forms of life during the Ediacaran-Cambrian transition which could be explained by two main hypotheses. One calls for a mass extinction, and others point to evolutionary processes causing the disappearance of Ediacaran forms of life (Narbonne 2005).

Whatever the cause, the extinction of life forms of Ediacaran was followed by an event known as the Cambrian explosion of life, consider one of the most significant events on the planet, after all, animals radiate for the first time on this planet (Marshal 2006, Mángano & Buaotis 2014). Although still controversial, there are two main causes that are favored to explain such an explosion of life. First, a small increase in the oxygen concentration in the atmosphere, not to the levels observed today, but high enough to provide enough energy to foster the appearance of more complex animals (Canfiled et al. 2007, Sperling et al. 2013). Among newcomers, the emergence of carnivore animals and related predation burst a series of morphological and behavioral strategies that lead to more complex ecosystems with more structured food chains. There was the appearance of sediment engineers causing bioturbation, leading to an increase of oxygenation deep in the sediments, coupled with essential nutrients like N and P to the water column (Mángano & Buatois 2014). This oxygenation favors aerobic organisms as well as a faster decomposition of the organic matter, releasing key nutrients to fuel new photosynthesis (Erwin & Tweed 2012). The changes in biodiversity between Ediacaran and Cambrian deeply affected the nutrient cycling of carbon, nitrogen, phosphorus, and sulfur in the ocean (LaPorte et al. 2009, Maloof et al. 2010, Ader et al. 2014, Laasko et al. 2020). For instance, there were large fluctuations in the $\delta^{13}C$ of calcium carbonate and in the $\delta^{13}C$ of associated organic matter, indicating large swings in the relative importance between dissolved inorganic carbon (DIC) and organic carbon produced by photosynthesis and decomposed along the water column (Maloof et al. 2010). Changes in the redox conditions due to the oxygenation of the oceans in the Ediacaran and Cambrian lead to more stable conditions for the preservation of nitrate in the water column (Ader et al. 2014). Finally, during the Ediacaran period, there was a large change in the phosphorus budget of the ocean not related to the increase of erosional P, but, indeed, due to the surge of sulfate-reducing bacteria leading to the remineralization of organic P by this group of bacteria (Laasko et al. 2020).

After the Cambrian explosion, a second burst of the diversity of life appeared in the Ordovician Period, the Great Ordovician Biodiversification Event (GOBE). The main feature of this event was the diversification at the genus, family, and species levels since most phyla were already presented after the Cambrian explosion (Harper 2006, Algeo et al. 2016). Of great importance to the biogeochemical cycles was the phytoplankton revolution, feeling the whole water column with a burst of life, followed by zooplankton and an entirely new marine food chain. Partially, such changes were catalyzed by high nutrient inputs due to volcanic activity, evidencing once more the coupling of geochemical and biological processes (Servais et al. 2009). The two major consequences of the phytoplankton growth were one of the largest burials of carbon in marine sediments, and an increase in the atmospheric O_2 concentration (Algeo et al. 2016). This exemplifies one possible mechanism of feedback between geological and biological processes that occurred during the Planet's evolution. An influx of nutrients caused by geotectonic processes leads to a flourishing of life in the marine water column, that in turn increases carbon burial and increases the atmosphere's oxidation.

The Cambrian explosion and the GOBE set a new stage in marine ecosystems adding complexity to trophic interactions never seen before. However, these whole new ecosystems collapse due to the first of five big extinction events, the End of Ordovician crises (Bond & Grasby 2017). The cause for such a catastrophic event is still debatable but whatever the cause, more than 85% of marine animals' invertebrate species disappeared (Brenchley et al. 2001). Some studies advocate global cooling leading to an abrupt decrease in the sea level (Hirnantian glaciation). Probably this glaciation was caused by (i) the consumption of CO_2 in the weathering of freshly exposed rocks of the newly formed mountains in several parts of the world (Ernest & Youbi 2017), (ii) the intense phytoplankton photosynthesis, that occurred during the GOBE (Algeo et al. 2016); and (iii) by the origination and expansion of the first land plants of the Planet that accelerated silicate weathering, consuming CO_2 (Lenton et al. 2012). With the end of the Hirnantian glaciation and the warming of the Earth, the second pulse of extinction occurred killing cool water specialists (Bond & Grasby 2017). An alternative explanation of the Late Ordovician extinction was posed recently by Bond & Grasby (2020). To these authors, the cause of this extinction is not different from the other four to follow. A combination of volcanism, warming, not cooling, and anoxia was the culprit. Whatever the causes, it seems that in a relatively geologically short period of time (4-5 Ma) there was a full recovery with few bursts of biodiversity; therefore, the Silurian Period fauna was like the Late Ordovician Period (Brechley et al. 2001).

The following bid extinction was the Late Devonian (LD) events, which were a series of events that occurred during this period. These events are linked with fluctuation of sea level, anoxic ocean events, and volcanism in the Viluy traps, located in eastern Siberia (Ricci et al. 2013, Ernst & Youbi 2017, Bond & Graspy 2017). However, the news of the LD is the possible role that terrestrial rooted plants had played. Algeo et al. (1995, 1998), proposed that vascular land plants, which seem to be originated in the middle Cambrian–Early Ordovician (Morris et al. 2018), played an important role in the LD crisis. Rooted trees accelerated soil formation and weathering of silicates, consuming atmospheric CO_2 in these reactions, leading to global cooling. The weathering process also increases the nutrient flux to the ocean, causing eutrophication and anoxia.

Therefore, the domination of continents by vascular land plants, has important implications for the carbon and oxygen global biogeochemical cycles, causing a major ecological crisis in the Late Devonian (McGhee et al., 2013). Literally, vascular land plants caused the almost total disappearance of fish like the placoderm, an iconic predator of the Late Devonian Period (Friedman & Sallan 2010). However, the LD extinctions had a significant impact on the evolution of vertebrates, the placoderms were replaced by chondrichthyans, actinopterygians, and tetrapods (Sallan & Coates 2010).

However, worse was yet to come in terms of biotic crisis, at the end of the Permian Period, when there was a >90% loss of marine species, coupled with severe species losses on land; ranking this event as the most destructive of all Big Five (McGhee et al. 2013). It seems that it all started with the volcanism generated by the formation of the Siberian Traps, liberating CO_2 to the atmosphere, causing global warming, followed by oceanic anoxic episodes that resulted in the release of toxic hydrogen sulfide (H_2S) produced by sulfate-reducing bacteria, with strong implications for the survival of several species (Kump et al. 2005). Likely candidates of killing mechanisms also include ocean acidification due to the increased CO_2 in the atmosphere, ozone depletion leading to a lethal increase of UV-B radiation, acid rain, and the release of toxic metals in the ocean (Bond & Grasby 2017).

The recovery of biodiversity from this major biotic crisis took a long, but during the middle of the Triassic, life on the planet recovered just to face a new important biotic crisis at the end of the Triassic (ET). Again, volcanism was the main culprit, this time mostly from the Central Atlantic Magmatic Province, again large amounts of CO_2 were emitted to the atmosphere triggering the anoxia-acidification process, responsible for an important ecological crisis on the planet (McGhee et al. 2013). Finally, the Cretaceous-Paleogene (K-Pg) extinction was the last of the Big Five, it is a popular event because was responsible for the extinction of non-avian dinosaurs (Chiarenza et al. 2020, but see Sakamoto et al. 2016, Condamine et al. 2021 for alternative hypothesis), and because of the extinction of several species of well-known taxa like plants, birds, fish, and insects (e.g., Longrich et al. 2011). There are two main plausible causes for the K-Pg, one is the trivial biogeochemical (warming-anoxia-acidification) process triggered by volcanism of the Deccan Traps, in north India (Wignall 2001, Chenet et al. 2007); and the second was an extra-terrestrial cause, a collision of a meteor that occurred in the Chicxulub peninsula of Mexico (Alvarez et al. 1980, Schulte et al. 2010). In this last scenario, the impact was enough to shut down photosynthesis at the global level, causing a mass extinction of herbivores (Alvarez et al. 1980).

Until the recent discovery of several proto-mammalians fossils, mainly in China, it was believed that the displacement of non-avian dinosaurs opened an ecological void that was fulfilled by mammals. However, these recent discoveries cast doubts about this hypothesis since mammalians were wandering on the planet much before than earlier taught. Nonetheless, mammalians developed and irradiated giving origin to many species, including us, that in a geologically short time became a dominant species that altered the face of the Earth. The human endeavor was strong enough for some authors to propose that we initiated the sixth species extinction on the planet (Ceballos et al. 2015).

It is clear from the discussion above that life and biogeochemical cycles co-evolved through the history of the planet. The bursts of life or almost total extinctions on the planet were caused by major geochemical changes, that in turn were affected by different forms of life that evolved. So far, the planet faced five major extinction events; however, several authors are arguing that we are heading to a sixth extinction, this time caused mainly by a dominant species on the Earth, ourselves. We not only destroyed habitats in every corner of the planet, but we also injected CO_2 into the atmosphere by burning fossil fuels and burning forests, causing planetary warming with several unattended consequences, including major changes in several organisms. Therefore, the coupling of fragile ecosystems due to persistent land-use changes and global warming is triggering a possible new era of extinction of life on Earth.

The Anthropocene

The extinction of species was not the only environmental problem caused by our species. The *Homo sapiens* captured a big share of the Earth's primary productivity, profoundly changing the land cover of the planet, and causing long-lasting alterations in the biogeochemical cycles. The loss of species translates into a loss of functional diversity, precluding ecosystems to provide several services essential for humans (Cardinale et al. 2012, Dirzo et al. 2014). However, the full extension of defaunation of the Anthropocene in nutrient processing is still to be described (Young et al. 2016). What we have so far are examples at local scales of such effects. For instance, Bello et al. (2015) concluded that the loss of large seeds dispersers in the Brazilian Atlantic Forest would cause the loss of several large tree species, which ultimately would decrease the carbon storage. A similar conclusion was reached by Peres et al. (2016) by modeling the loss of seed-dispersal animals by overhunting in the Amazon region. Although noted directly addressed by these authors, carbon processing is so intrinsically connected with nitrogen that is reasonable to conclude that the processing of this nutrient would be also affected in these forests. This is the case of an exclusion experiment of large ground-dwelling frugivores in the Atlantic Forest, where the presence of large frugivores, like the tapir, increased the nitrogen availability (Villar et al. 2021).

At the global level, the burning of fossil fuels can be viewed as an acceleration of the geochemical carbon cycles by launching into the atmosphere carbon locked in the interior of the planet, which was produced by photosynthesis millions of years ago, transported to the ocean and buried in sediments. In this way, the burning of fossil fuels by humans is equivalent to vulcanism on a much faster scale. Consequently, CO_2 is building up in the atmosphere, increasing the temperature of the planet with a myriad of catastrophic consequences, including the survival of several species. A typical example is the acidification of the oceans, by increasing the transfer of CO_2 from the atmosphere into the ocean. Abrupt and fast changes in pH cause several harms to the maritime organisms, one of them is the dissolution of corals, which are one of the most biodiverse ecosystems in the world.

From this brief description of the N cycle made before, new reactive N supplied by NBF was the only way that inert N_2 was transformed into reactive N for several thousands of years. This changed between the first and second world wars with the Haber-Bosch process, which synthesizes ammonium from N_2 under high pressure and temperature. This process gave origin to the mineral fertilizers, that after the second world war, started to be massively used in food production.

Nitrogen fertilizers are the typical example of "too much of a good thing". If on the one side, the use of fertilizers allowed a large increase in food production, sustained an impressive population growth; on the other hand, the excess nitrogen from the excess use of mineral fertilizers caused several environmental problems in the atmosphere, soil, and water. Examples of N pollution by fertilizers: in water bodies, the excess of N stimulates the growth of algae followed by an O_2-demanding decomposition process, leading to anoxia with deleterious consequences to aerobic organisms; in soils, part of the N which is not absorbed by plants is converted to NO_3 and denitrified to N_2O, which is a potent greenhouse gas.

Besides pollution, excess N also can have a severe effect on biodiversity, the increased atmospheric N deposition in strongly N-limited ecosystem is altering the distributions of species since species more adaptable to an N-rich world can outcompete less adaptable species (Bobbink et al. 2010). In turn, the loss of species can further change the nitrogen dynamic in the soil-plant continuum (Villar et al. 2021). Land-use changes have also driven the nitrogen global cycle by cropping N-fixing Fabaceae species like soybean (Galloway et al. 2003). N-rich leaves of Fabaceae species decompose faster than other species, making available nutrients to the soil biota and the adjacent vegetation.

Associate Editor

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Conflicts of Interest

The authors declare that they have no conflict of interest related to the publication of this manuscript.

Ethics

This study did not involve human beings and/or clinical trials that should be approved by one Institutional Committee.

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