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Bioavailability of Phosphorus in Marine Ecosystems: Sources, Transport, and Ecological Impacts

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Abstract Phosphorus is an indispensable nutrient element in Marine ecosystems and plays a key role in the Marine food web and biogeochemical cycles. Phosphorus in the ocean exists in various chemical forms and is constantly cycled and transformed through biological and abiotic processes. This study Outlines the main sources of Marine phosphorus and its migration and transformation mechanisms in the Marine environment. The key environmental and biological factors influencing the bioavailability of phosphorus were analyzed. By comparing the relationship between primary productivity and phosphorus limitation in different sea areas, and combining regional cases such as the Mediterranean Sea, the South China Sea, and the North Atlantic, the impact of phosphorus supply changes on plankton communities and ecosystems is revealed. Finally, the evolution trend of the Marine phosphorus cycle under the background of global change and human activities is discussed, as well as the problems of eutrophication and red tides caused by phosphorus excess. The future research and management of the Marine phosphorus cycle are also prospected.

Keywords Marine phosphorus cycle; Bioavailability; Phosphorus limitation; Primary productivity; Eutrophication

1 Introduction

The importance of phosphorus (P) to Marine life is almost self-evident. It, like nitrogen (N) and carbon (C), is the most fundamental nutrient for life activities, but its role is more inclined to be a "connector between energy and genetics". The key molecules such as DNA, RNA and ATP all rely on the participation of phosphorus. Even the cell membrane needs phospholipids to maintain structural stability (Murphy et al., 2021). However, phosphorus is not always an abundant resource in the ocean. Often, it is the "bottleneck" for the growth of phytoplankton. Once there is a shortage of available phosphorus, the efficiency of photosynthesis will decline, and the chain effect will eventually be passed on to higher trophic levels. In contrast, there is a gaseous exchange pathway in the nitrogen cycle, while there is no such link in the phosphorus cycle. It mainly flows back and forth between the hydrosphere and the lithosphere in the form of dissolved and particulate states (Jin et al., 2024). As for the supply of phosphorus in the ocean, it mainly depends on two aspects: terrestrial transport and internal regeneration. Any fluctuation in any link will affect the balance of the entire ecosystem.

On a global scale, the picture of the phosphorus cycle is more like a long-term "deposition and regeneration" game. Rock weathering and river transportation are the starting points of most Marine phosphorus. After entering the ocean, phosphorus does not exist in isolation but is classified into various forms such as dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP), and particulate phosphorus, constantly flowing through absorption, sedimentation, and decomposition. In the vertical direction, phosphorus in surface seawater is often rapidly consumed by phytoplankton, while in the deep layer, more phosphate accumulates due to the decomposition of organic matter (Zhao et al., 2020). When the upwelling brings these phosphorus-rich water bodies back to the surface, the "biological pump" cycle is completed. However, this cycle is not balanced across different sea areas: for instance, the phosphorus concentration in the deep water of the Pacific Ocean is usually higher than that in the Atlantic Ocean, which is the result of long-term accumulation. Overall, phosphorus remains in the ocean for an extremely long time, often for tens of thousands of years, but this does not mean that it is evenly distributed. On the contrary, regional differences are obvious. In some areas, phosphorus is almost depleted, while in others, it is enriched due to geological or hydrological conditions (Zhang et al., 2025).

The research on the bioavailability of Marine phosphorus has long trantioned academic discussions in significance. As a key limiting element, phosphorus almost determines the upper limit of primary productivity and also shapes the structure of ecosystems. Clarifying the utilization methods and control mechanisms of different forms of phosphorus can not only explain the community turnover of phytoplankton but also help understand the changes in Marine carbon sinks. In reality, human influence has long permeated this cycle. The use of chemical fertilizers and the discharge of sewage have led to a continuous increase in the phosphorus load of coastal water bodies, causing eutrophication and even ecological disorders (Hao et al., 2025); Meanwhile, atmospheric deposition and climate change are rewriting the phosphorus input pattern in the distant-water areas, causing some sea areas that were originally nitrogen-restricted to gradually shift towards phosphorus-restricted. For this reason, the research on the bioavailability of phosphorus is not only related to theoretical improvement, but also to Marine management and climate response.

2 Chemical Forms and Distribution Characteristics of Phosphorus in the Ocean

2.1 Main components and transformations of inorganic and organic phosphorus

Phosphorus in the ocean can be divided into two major categories: inorganic phosphorus and organic phosphorus. Inorganic phosphorus mainly refers to dissolved inorganic phosphorus (DIP, that is, phosphate ions), which can be directly absorbed and utilized by phytoplankton and microorganisms. Organophosphorus includes dissolved organophosphorus (DOP) and granular organophosphorus (POP), which exist in organic molecules and decomposition products in organisms. Generally, it needs to be converted into inorganic phosphorus through enzymatic hydrolysis before it can be assimilated (Murphy et al., 2021). Marine organisms absorb DIP and construct phosphorus into their own organic matter. When organisms die or excrete, DOP and POP are produced. After microbial decomposition, phosphate is released again, achieving the re-conversion of organic phosphorus to inorganic phosphorus (Jin et al., 2024). In addition, under specific conditions, phosphates in the environment can combine with metal ions and precipitate into granular inorganic phosphorus (such as apatite), which then settles to the seabed.

2.2 Vertical distribution and spatiotemporal variation patterns of phosphorus in seawater

The vertical distribution of phosphorus in Marine water bodies shows a typical feature of being low in the surface layer and high in the deep layer: the phosphorus concentration in the surface layer is often close to depletion due to the rapid absorption by phytoplankton. In the middle and deep layers, due to the decomposition of settled organic particles, inorganic phosphates are released, making the deep seawater rich in phosphorus (Duhamel, 2024). During seasonal changes, vertical mixing of seawater in winter can bring deep phosphorus to the surface layer, temporarily increasing the phosphorus content in the surface layer. In spring and summer, phytoplankton multiply vigorously and consume a large amount of phosphorus, causing the surface layer to become scarce again. In terms of spatial scale, there are significant differences in phosphorus levels among different sea areas: The surface phosphorus concentration is relatively high in coastal and estuarine areas due to river input and upwelling (Brady et al., 2022); On the contrary, in closed waters such as the subtropical circulation center of the open sea, the surface phosphorus level is extremely low throughout the year. Due to the limitations of light or iron in high-latitude seas, phytoplankton do not fully utilize phosphorus, and a certain amount of phosphate is often retained in the surface layer.

2.3 Differences in phosphorus dynamics among various ecological zones

There are obvious differences in the dynamics of phosphorus cycling in different ecological regions of the ocean. Coastal and estuarine areas are strongly influenced by terrigenous substances, and the phosphorus concentration in water bodies fluctuates with the seasons and human activities: During the wet season, river runoff carries a large amount of inorganic phosphorus and particulate phosphorus, leading to a sharp increase in local phosphorus content. The input decreased during the dry season and the phosphorus concentration dropped (Zhang et al., 2025). In contrast, in oligotrophic sea areas such as oceanic circulation centers, phosphorus supply is chronically scarce and changes gently. Ecosystems can only rely on mechanisms such as microbial loops to repeatedly recycle trace amounts of phosphorus. In the upwelling area, due to the influx of deep phosphorus-rich seawater, the surface phosphorus is relatively abundant, maintaining high primary productivity. However, in some semi-enclosed sea areas with severe stratification (such as deep water anoxic basins), phosphorus accumulates in large quantities in the deep layers but cannot be replenished to the surface, resulting in a pattern of phosphorus-poor upper layers and phosphorus-rich deep layers (Zeng et al., 2022). Due to the differences in hydrological, topographic and biological factors, the phosphorus cycle in different ecological zones shows unique dynamics, which require separate studies for specific environments.

3 Major Sources of Marine Phosphorus

3.1 Terrestrial inputs: river runoff, agricultural, and industrial discharges

Land-based input is an important exogenous source of Marine phosphorus, among which river runoff plays a key role. Phosphate released from the weathering of terrestrial rocks flows into the ocean via rivers. Meanwhile, a large amount of phosphorus-containing pollutants produced by human agricultural fertilization, animal husbandry and industrial life emissions are also carried into the coastal areas through rivers. The phosphorus output in modern river basins has significantly increased compared to the natural situation, resulting in a significant increase in the phosphorus load of estuarine and nearshore water bodies (Jin et al, 2024). A portion of the phosphorus transported by rivers exists in dissolved form and can be directly utilized by Marine organisms. Another part was adsorbed on the sediment and deposited in estuaries and continental shelves in the form of granular phosphorus (Wang et al., 2021). An appropriate amount of phosphorus input can support high primary productivity and fishery resources along the coast, but excessive phosphorus can cause environmental problems such as eutrophication, algal blooms and even hypoxia. Therefore, the input of land-based phosphorus plays a profound role in regulating the coastal ecosystem, and its control is crucial for maintaining the Marine ecological balance.

3.2 Atmospheric deposition and phosphorus transport via dust

In the sea far from the shore, people often rely on things that fall from the sky to get some nourishment. The wind sweeps up dust from the arid continent, which contains phosphorus mineral particles. After transoceanic flight, it falls into the sea, adding a handful of phosphorus to the surface water (Dam et al., 2021). The example in the North Atlantic is quite intuitive: Sahara dust not only brings phosphorus but also iron, benefiting phytoplankton. However, not all the phosphorus that falls is effective. Most of the phosphorus in mineral dust is in insoluble inorganic form. However, during flight, acidic gases are encountered. Some of the phosphorus is "pre-treated" and becomes soluble, making it easier for organisms to utilize (Hu et al., 2025). In recent years, the climate has been changing, and so has the dust: drier continents and stronger winds may increase the output of dust. However, when the temporal and spatial distribution of rainfall changes, the rhythm of sedimentation also becomes disrupted. The result is that the way and intensity of phosphorus reception in the open sea areas have been rewritten, and primary productivity and carbon sink capacity may also fluctuate accordingly.

3.3 Contributions from seafloor geological processes and sediment release

There are also mechanisms for the release of phosphorus through geological and sedimentary processes within the ocean. Submarine volcanic eruptions and hydrothermal activities release phosphorus-containing substances into seawater. Although this part of the flux is relatively small and localized, it may contribute to the surrounding phosphorus levels in areas with frequent volcanic activities (Liu et al., 2023). More commonly, there is the re-release of phosphorus from sediments: the ocean uses biological pumps to deposit large amounts of phosphorus on the seabed, and sediments become huge phosphorus reservoirs. When the bottom water body is hypoxic, phosphorus combined with oxides such as iron in the sediment is desorbed due to reduction and diffuses into the overfacing seawater (Guo et al., 2020); Phosphorus produced by the decomposition of organic matter can also be released into the water column from pore water. The disturbance of benthic organisms can also bring out some buried phosphorus and integrate it into the cycle. However, most of the phosphorus that enters the sediment is eventually fixed and buried in the geological layer in the form of minerals, so the seabed process is generally the "destination" of Marine phosphorus. Only a small amount of sedimentary phosphorus released under special conditions remains an indispensable part of the nutrient supply in some local sea areas.

4 Transport and Transformation Mechanisms of Phosphorus in the Marine Environment

4.1 Transport pathways of dissolved and particulate phosphorus

The migration of phosphorus in the ocean occurs through two pathways: dissolved state and particulate state. Dissolved phosphorus (including DIP and soluble DOP) spreads with the flow of seawater: Ocean currents and upwelling transport phosphorus-rich water masses to other areas, and vertical mixing carries deep dissolved phosphorus to the surface (Murphy et al., 2021). These hydrodynamic processes shape the large-scale distribution pattern of phosphorus. In contrast, granular phosphorus mainly migrates along the vertical direction through gravitational sedimentation. Organic debris particles formed by plankton sink downward, transporting phosphorus from the surface to the deep sea. This "biological pump" process causes surface phosphorus to continuously move out and accumulate in the deep sea (Browning et al., 2017). Some of the sinking particles are decomposed during the process, and the phosphorus assimilated re-dissolves into the surrounding water body. The undecomposed ones eventually sink into the seabed sediments. In addition, phosphorus-containing sediment suspended in coastal waters can also be carried by coastal currents and transported horizontally near the bottom layer. The long-distance transport in dissolved form and the sedimentation in granular form jointly determine the spatiotemporal redistribution of Marine phosphorus.

4.2 Microbially driven degradation and remineralization of organic phosphorus

The degradation and remineralization of organic phosphorus in the ocean are highly dependent on microbial activities. Heterotrophic bacteria and other microorganisms secrete phosphatases that hydrolyze DOP into inorganic phosphates, converting the originally unusable organic phosphorus into an absorbable form. When phosphorus is scarce, many phytoplankton and microorganisms can significantly increase the production and activity of alkaline phosphatase (AP), "extracting" phosphorus from the surrounding organic matter and alleviating environmental phosphorus limitation. In the sediment, a large amount of buried organic phosphorus is also decomposed under the action of anaerobic microorganisms, releasing phosphorus into the pore water and then diffusing into the overlying water body. The degradation rate of microorganisms is affected by environmental conditions: the higher the temperature, the faster the decomposition of organic matter and the remineralization of phosphorus. Oxygen conditions determine the decomposition pathways and efficiencies of certain organophosphorus compounds (Duan et al., 2025).

4.3 Phosphorus release and regeneration at the sediment–water interface

The sediment-water interface is an active exchange site in the phosphorus cycle. After phosphorus-containing particles sink to the seabed, some of the phosphorus in them can be re-released into the water body at the interface. On the one hand, the sedimentary organic matter is decomposed by anaerobic microorganisms, and phosphate is released into the pore water of the sediment and diffuses along the concentration gradient to the bottom seawater (Jin et al., 2024). On the other hand, when the bottom water is oxygen-deficient, the iron and manganese oxides that originally adsorbed phosphate in the sediment are reduced and dissolved, and the phosphorus bound to them is desorbed and released into the water. Under oxidative conditions, the opposite process occurs: phosphorus is readily adsorbed and fixed by metal oxides in sediments to form precipitates (Randolph-Flagg et al., 2023). Periodic disturbances (such as storms and benthic activities) can enhance interfacial exchange, enabling phosphorus released from sediments to enter the overlying water layer cycle more quickly. Phosphorus regeneration at the sediment-water interface regulates the nutrient supply of bottom water and surface water at a local scale: in eutrophic waters, it can act as an internal phosphorus source, intensifying phosphorus accumulation in the water body. When in overall equilibrium, sediments tend to act as terminal sinks for phosphorus.

5 Key Environmental and Biological Factors Affecting Phosphorus Bioavailability

5.1 Regulatory roles of physicochemical conditions

The physicochemical conditions of the Marine environment regulate the bioavailability of phosphorus by influencing its form and flow. The higher the temperature, the faster the rate of organic matter decomposition and phosphorus remineralization usually is, but the high stratification of seawater can also inhibit the transport of deep phosphorus to the surface. The pH value of water bodies affects the dissolution equilibrium of phosphorus: under acidic conditions, phosphate adsorbed on particles is more likely to be released into water, and in alkaline environments, phosphate tends to combine and precipitate with cations such as calcium and magnesium (Wu et al., 2021). The REDOX state is even more crucial: under oxygenated conditions, phosphorus is easily adsorbed and fixed by iron and manganese oxides. Once the environment turns oxygen-deficient, these oxides are reduced and dissolved, and the phosphorus adsorbed on them is released in large quantities, resulting in an increase in the phosphorus concentration of the surrounding water. Furthermore, the mixing condition of water bodies determines the efficiency of nutrient re-supply. Strong vertical mixing (such as storms, winter convection) can bring deep phosphorus sources back to the surface and alleviate surface phosphorus limitation (Zhou et al., 2021); Long-term stable stratification leads to the depletion of surface phosphorus without replenishment. The combined effect of these physical and chemical factors shapes the effective supply level of phosphorus in different regions and seasons.

5.2 Binding effects of metal ions, mineral particles, and organic matter

The activity of phosphorus in seawater is affected by its combination with various metals and particles. Phosphate has a strong affinity for metal oxides such as iron and aluminum, and is easily adsorbed on their surfaces or precipitated with calcium ions to form insoluble phosphate minerals, thereby removing phosphorus from the aqueous phase and turning it into a solid phase. This means that even if the total phosphorus content in the environment is not low, some of it may be fixed on particles and temporarily unavailable (Yan et al., 2022). Fine-grained sediment and clay minerals can also adsorb phosphate ions, causing phosphorus to settle with the particles (Brady et al., 2022). Dissolved organic matter can affect the availability of phosphorus through multiple effects: some organic colloids can combine with phosphorus to form complexes, hindering its direct uptake by organisms; Some organic ligands, when combined with metal ions, weaken the fixation effect of metals on phosphorus, indirectly increasing the bioavailable ratio of phosphorus.

5.3 Metabolic regulation by microbial communities and phytoplankton

When there is not enough phosphorus, Marine life will not just sit and wait to die. Phytoplankton usually "transform" themselves: reducing components with high phosphorus demands, such as replacing some membrane phospholipids with sulfur-containing lipids; It will also increase the production of phosphatase and "extract" some usable phosphorus from the surrounding DOP. Sometimes, when there is too much phosphorus, they will absorb a little more and stockpile polyphosphates to prepare for the subsequent "famine" (Fru et al., 2023). The appetite for phosphorus varies greatly among different organisms. Small phytoplankton, due to their large surface area and small volume, have a higher absorption efficiency and are often the winners in phosphorus-poor sea areas. Large algae grow fast but consume a lot. Once they lack phosphorus, they will fall behind. As for the internal part of the microbial community, it is not monolithic either. Bacteria can decompose organic matter and release phosphorus, providing nutrients for algae. But sometimes they also compete with algae for inorganic phosphorus, and this competition is no less intense (Zhang et al., 2025). Overall, both microorganisms and phytoplankton are making subtle metabolic adjustments to enable the ecosystem to respond flexibly to the amount of phosphorus, and as a result, the phosphorus utilization pattern of the entire ocean is constantly changing.

6 Relationship Between Marine Primary Productivity and Phosphorus Limitation

6.1 Effects of phosphorus limitation on phytoplankton growth and community structure

When the available phosphorus in seawater is lower than the demand of phytoplankton, both their growth rate and community composition will change. Insufficient phosphorus can slow down the cell division and photosynthesis of phytoplankton and cause physiological changes, such as depletion of intracellular phosphorus reserves and a decrease in photosynthetic pigment content. Some large populations that rely on high phosphorus (such as macrodiatoms) gradually decline under the condition of continuous phosphorus deficiency, while some small algae and blue-green algae that tolerate low phosphorus have the advantage with lower nutrient requirements and higher absorption efficiency, resulting in the succession of community structure towards miniaturization and low diversity (Figure 1) (Browning and Moore, 2023). Meanwhile, under phosphorus restriction, the intracellular carbon-phosphorus ratio (C:P) of phytoplankton cells increases, the nutritional quality declines, and the growth and reproduction of zooplankton may be hindered after feeding (Lin et al., 2023). It can be seen from this that the level of phosphorus supply directly affects the productivity and composition of phytoplankton and has a chain effect on higher trophic levels through food web transmission.

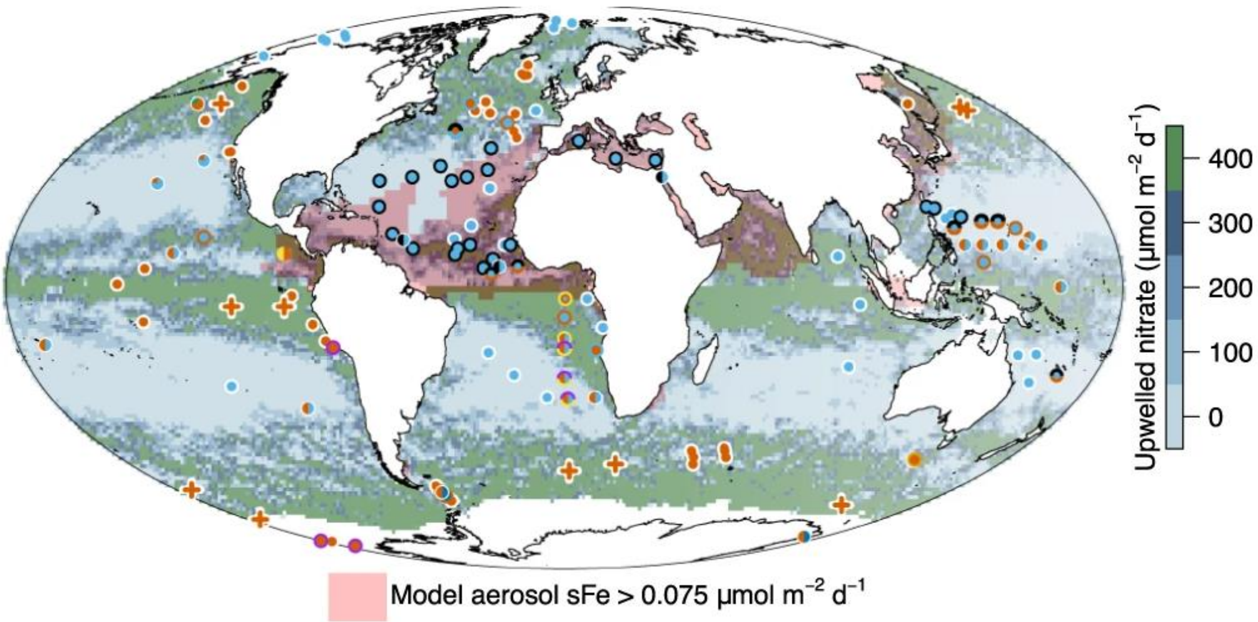

Figure 1 Experimentally derived nutrient limitation patterns on a background of estimated nitrate upwelling (Adopted from Browning and Moore, 2023)

6.2 Nutrient competition and adaptive mechanisms under phosphorus-limited conditions

In a phosphorus-deficient environment, various organisms fiercely compete for the limited phosphorus resources and simultaneously evolve multiple adaptive strategies. Phytoplankton have developed a high-affinity phosphorus uptake system and a "luxury absorption" mechanism: once there is a brief phosphorus input into the environment, they quickly absorb it and store it in the form of polyphosphates for later use (Wang, 2025). Heterotrophic bacteria gain a competitive edge under low DIP conditions by virtue of their ability to utilize organic phosphorus. They obtain phosphorus from dissolved organic matter, reducing their reliance on inorganic phosphorus. The competition between algae and bacteria depends on conditions: in phosphorus-poor water bodies rich in organic matter, bacteria often have the upper hand; In environments with abundant sunlight and fleeting DIP, algae seize the initiative (Zhang et al., 2022). To adapt to phosphorus deficiency, many algae secrete more phosphatases to break down environmental DOP or replace certain cellular components with phosphorus-free substances to reduce the phosphorus requirement. Some nitrogen-fixing cyanobacteria also reduce their nitrogen-fixing activity when phosphorus is insufficient, prioritizing the limited phosphorus for basic growth (Lin et al., 2023). Through these competitive and adaptive mechanisms, ecosystems can still maintain certain functional operations under severe phosphorus constraints.

6.3 Regional differences in phosphorus utilization across oceanic areas

Due to the different nutritional supply conditions, there are significant differences in the utilization strategies of phosphorus by plankton in various sea areas. In high-productivity seas such as coastal and upwelling areas, nitrogen is often the main limiting factor, while phosphorus is relatively abundant. Phytoplankton tend to grow rapidly and store excess phosphorus, and are not sensitive to phosphorus restrictions (Huang and Han, 2025). However, in the oligotrophic circulation centers of the ocean, the long-term low-phosphorus environment has created highly efficient "phosphorus-saving" communities: those plankton have an extremely high absorption affinity for trace phosphorus, can fully utilize DOP, and repeatedly recover phosphorus through the microbial loop, enabling the communities to operate at extremely low phosphorus concentrations (Jin et al., 2024). In addition, in some regions, due to high exogenous N input and a relatively large N-P ratio (such as the Mediterranean), phytoplankton, in order to adapt to the relatively phosphorus-deficient environment, will rely more on organic phosphorus and phosphatase pathways to obtain phosphorus.

7 Case Studies

7.1 The Mediterranean Sea: phytoplankton succession and community restructuring under strong phosphorus limitation

The Mediterranean Sea, especially the eastern waters, has long been in a state of severe phosphorus limitation. Due to the high input of land-based nitrogen, the nitrogen-phosphorus ratio in seawater far exceeds the Red Field ratio, with phosphorus becoming the main limiting nutrient. Vertical mixing at the end of winter and the beginning of spring brings a small amount of deep phosphorus to the surface, triggering a brief spring algal proliferation. Species such as small diatoms and dinoflagella, which are good at seizing phosphorus pulses, are dominant (Yuan et al., 2018). However, after the surface phosphorus is rapidly depleted, the system enters a state of phosphorus starvation. Large algae decline due to phosphorus deficiency, while small low-phosphorus tolerant species (such as microcyanobacteria, etc.) rise and dominate the summer and autumn communities. Phosphorus deficiency forces local phytoplankton to generally increase phosphatase activity and use DOP to maintain growth (Browning et al., 2017). The limitation of primary production leads to a low productivity of the entire food web. Occasionally, when additional phosphorus is injected into the Eastern Mediterranean by Sahara dust and the like, certain species that are usually restricted (such as nitrogen-fixing cyanobacteria and macrodiatoms) take the opportunity to break out and reshape the community in the short term (Mi et al., 2023). This indicates that in extreme phosphorus-constrained environments, plankton succession is highly sensitive to external nutrient input.

7.2 The South China Sea: impacts of terrestrial inputs and human activities on phosphorus fluxes

The South China Sea is a typical marginal sea and cannot do without the "gifts" of the land. Every year, major rivers such as the Pearl River and the Mekong River carry sediment and nutrients into the ocean, spreading a thick layer of nutritional background along the banks. Especially in the Pearl River Estuary area, agricultural runoff and urban sewage discharge have led to a continuous increase in the input of phosphorus year after year, and the load on water bodies has become increasingly heavy. The results are also obvious - frequent algal blooms and hypoxia at the bottom layer, these eutrophication signals have become more prominent in recent years (Carrillo et al., 2015). In contrast, in the open sea, the central part of the South China Sea was originally nutrient-poor. It is precisely these land-based inputs that have made up for some of its shortcomings. However, this kind of "supply" seems to have become unbalanced in recent decades. As the amount of phosphorus discharged by human activities continues to rise, the nitrogen-phosphorus ratio in some sea areas has been pushed up, and some areas that were originally nitrogen-restricted have instead become phosphorus-restricted. Phytoplankton also responded - their phosphorus-obtaining enzyme activity was significantly enhanced, showing characteristics adapted to phosphorus-poor environments (Figure 2) (Mi et al., 2023; Jin et al., 2024). From this example, it can be seen that the dual effects of terrestrial materials and human activities are reshaping the phosphorus cycle and nutrient structure in the South China Sea, and also posing new challenges to the stability of coastal ecosystems.

7.3 The North Atlantic: alterations in phosphorus cycling induced by climate warming and atmospheric deposition

The North Atlantic has somewhat "changed" in recent years. The impact of warming is first reflected in the intensification of stratification - the mixture of seawater from top to bottom is no longer as thorough, making it difficult for deep phosphorus to be brought up, and thus the supply from the surface is tightened. In winter and spring, water bodies that should be rich in phosphorus become "thin", and primary productivity is also affected accordingly. Meanwhile, a large amount of nitrogen-containing compounds released by human activities are deposited into the North Atlantic through the atmosphere. The input of nitrogen is much higher than that of phosphorus, causing the nitrogen-phosphorus ratio of surface water to rise continuously. Some once typical nitrogen-restricted sea areas have now become phosphorium-scarce zones - there is still a considerable amount of nitrate left, but phosphate is almost depleted. This is precisely the side effect of excessive exogenous nitrogen (Trombetta et al., 2019). This change reminds us that climate warming and atmospheric deposition are not acting independently but are jointly driving the North Atlantic to shift from nitrogen limitation to phosphorus limitation. This case not only reveals the fragile balance of the Marine nutrient structure, but also provides a realistic reference for understanding the coupling effect of global warming and human pollution.

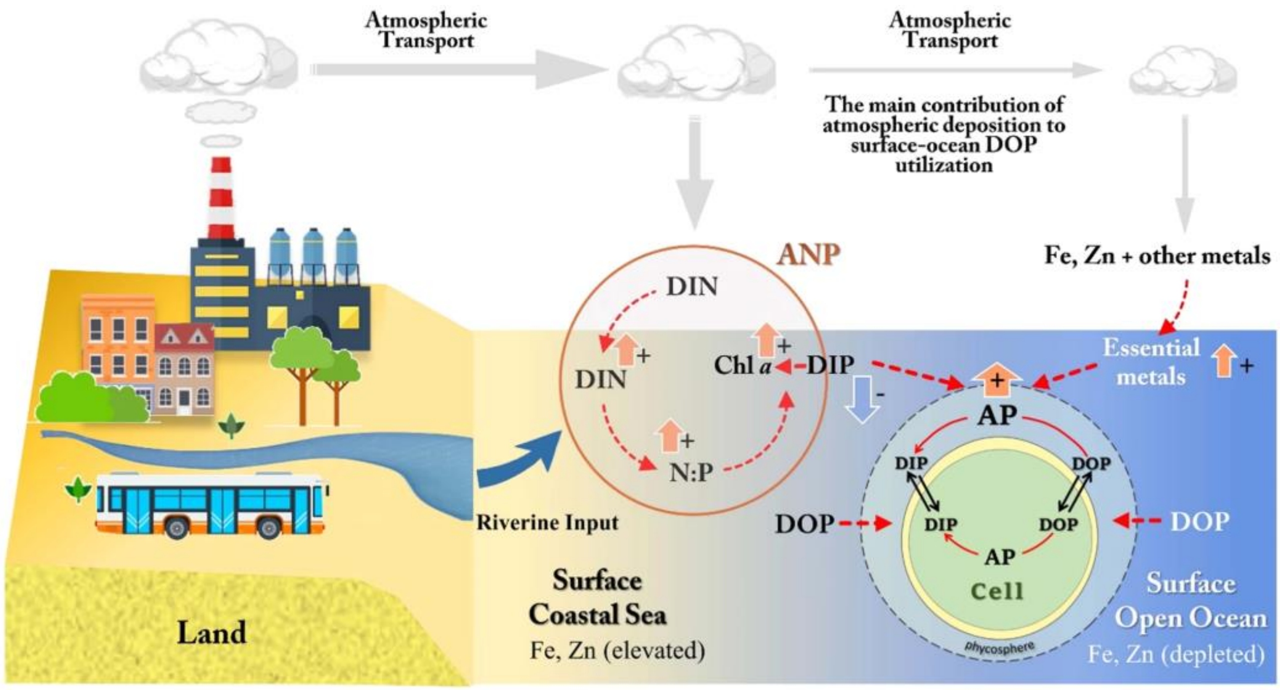

Figure 2 Conceptual diagram of the anthropogenic nitrogen pump (ANP) (Adopted from Jin et al., 2024)

8 Ecological Effects of Changes in the Marine Phosphorus Cycle

8.1 Impacts on food web structure and trophic transfer

Changes in Marine phosphorus supply often spread throughout the food web by affecting primary producers. Insufficient phosphorus supply leads to a decrease in phytoplankton biomass or changes in community composition, and the number of zooplankton dependent on them also decreases accordingly, which in turn affects higher trophic food sources such as fish, and may cause attenuation of fishery resources and reduction of biodiversity (Boxhammer et al., 2018). On the contrary, eutrophication caused by excessive phosphorus input will lead to the abnormal reproduction of a few high-nutrient-tolerant algae, forming a single dominant population. This algal bloom outbreak disrupts the normal food web structure: a large number of algae sink and decay due to the lack of sufficient consumers, resulting in hypoxia at the bottom and massive deaths of benthic organisms and fish (Paerl et al., 2018); Even in the absence of extreme events, if the composition of phytoplankton in a high-phosphorus environment leans towards species with lower nutritional value, it will also reduce the efficiency of trophic level transfer.

8.2 Interactions and feedback mechanisms among phosphorus, carbon, and nitrogen cycles

In the ocean, phosphorus is not a lone fighter; it is always entangled with its two old partners, carbon and nitrogen. For phytoplankton to absorb carbon dioxide, they need sufficient phosphorus as support. If there is not enough phosphorus, even if there is a lot of nitrogen, they won't be able to do the job, and the absorption of CO_2 will naturally be reduced. However, once there is an increase in phosphorus in the environment, such as the "easy delivery" input brought by dust, phytoplankton can immediately accelerate, fix more carbon, and then send it to the deep sea through the biological pump (Zhou et al., 2023). Phosphorus is also indispensable for nitrogen fixation. Those microorganisms that can "produce nitrogen" themselves require a large amount of energy, and phosphorus is precisely a key link in energy metabolism. Without it, the nitrogen fixation rate drops immediately, and the entire system's ability to "generate new nitrogen" weakens accordingly. The problem is that humans are discharging more and more nitrogen into the atmosphere, but the increase in phosphorus is not keeping up. As a result, the N:P ratio in the ocean surface is increased, nitrate accumulates and is unused, and is eventually released back into the atmosphere through processes such as denitrification (Hayat et al., 2025). From this perspective, phosphorus is somewhat like an invisible "gate", which precisely controls the ocean's response to greenhouse gases and also influences the balance of carbon and nitrogen in the sea.

8.3 Eutrophication and harmful algal blooms caused by excessive phosphorus input

Under the influence of human activities, many nearshore and semi-enclosed water bodies have experienced frequent eutrophication and harmful algal blooms due to excessive phosphorus input. Phosphorus is often one of the key drivers contributing to the overgrowth of algae: When estuaries and bays receive high concentrations of phosphorus from agricultural fertilizers and urban sewage, algae can take up nitrogen together and multiply rapidly, forming algal blooms or "red tides" (Gao et al., 2025). Some cyanobacteria can stand out under phosphorus-rich and low N:P conditions, and their nitrogen fixation function enables them to multiply on a large scale without being restricted by nitrogen supply. Such algal blooms not only deteriorate water quality and reduce transparency, but also consume oxygen in the water, causing hypoxia at the bottom and the death of organisms. More seriously, the hypoxic environment caused by eutrophication will prompt the sediment to release more phosphorus (increased internal load), which further promotes the next round of algal bloom, forming a vicious cycle (Xiao et al., 2019). Once this happens, it is very difficult for the water body to restore itself to a low nutritional level. Therefore, to prevent and control Marine eutrophication, it is essential to focus on reducing phosphorus emissions at the source and supplement it with ecological restoration and other measures to break the positive feedback of the phosphorus cycle, reduce the risk of red tides, and maintain the health of coastal ecosystems.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Boxhammer T., Taucher J., Bach L., Achterberg E., Algueró-Muñíz M., Bellworthy J., Czerny J., Esposito M., Haunost M., Hellemann D., Ludwig A., Yong J., Zark M., Riebesell U., and Anderson L., 2018, Enhanced transfer of organic matter to higher trophic levels caused by ocean acidification and its implications for export production: A mass balance approach, PLoS ONE, 13(5): e0197502.
https://doi.org/10.1371/journal.pone.0197502

Brady M., Tostevin R., and Tosca N., 2022, Marine phosphate availability and the chemical origins of life on Earth, Nature Communications, 13: 5162.
https://doi.org/10.1038/s41467-022-32815-x

Browning T., and Moore M., 2023, Global analysis of ocean phytoplankton nutrient limitation reveals high prevalence of co-limitation, Nature Communications, 14: 5014.
https://doi.org/10.1038/s41467-023-40774-0

Browning T., Achterberg E., Yong J., Rapp I., Utermann C., Engel A., and Moore M., 2017, Iron limitation of microbial phosphorus acquisition in the tropical North Atlantic, Nature Communications, 8: 15465.
https://doi.org/10.1038/ncomms15465

Carrillo P., Medina-Sánchez J., Herrera G., Durán C., Segovia M., Cortés D., Salles S., Korbee N., Figueroa F., and Mercado J., 2015, Interactive effect of UVR and phosphorus on the coastal phytoplankton community of the Western Mediterranean Sea: unravelling eco-physiological mechanisms, PLoS ONE, 10(12): e0142987.
https://doi.org/10.1371/journal.pone.0142987

Dam T., Angert A., Krom M., Bigio L., Hu Y., Beyer K., Mayol-Bracero O., Santos-Figueroa G., Pio C., and Zhu M., 2021, X-ray spectroscopic quantification of phosphorus transformation in saharan dust during trans-atlantic dust transport, Environmental Science and Technology, 55(18): 12694-12703.
https://doi.org/10.1021/acs.est.1c01573

Duan Z., Liang J., Shi L., Xu Y., Gao W., and Tan X., 2025, Eutrophication heterogeneously enhances organic matter and phosphorus exchanges among dissolved particulate and sedimentary phases in a large shallow lake, Environmental Science and Technology, 59(26): 13264-13274.
https://doi.org/10.1021/acs.est.4c12091

Duhamel S., 2024, The microbial phosphorus cycle in aquatic ecosystems, Nature Reviews, Microbiology, 23(4): 239-255.
https://doi.org/10.1038/s41579-024-01119-w

Fru E.C., Bahri J., Brosson C., Bankole O., Aubineau J., Albani A., Nederbragt A., Oldroyd A., Skelton A., Lowhagen L., Webster D., Fantong W., Mills B., Alcott L., Konhauser K., and Lyons T., 2023, Transient fertilization of a post-Sturtian Snowball ocean margin with dissolved phosphate by clay minerals, Nature Communications, 14: 8418.
https://doi.org/10.1038/s41467-023-44240-9

Gao J., Mang Q., Li Q., Sun Y., and Xu G., 2025, Microbial-algal symbiotic system drives reconstruction of nitrogen phosphorus and methane cycles for purification of pollutants in aquaculture water, Bioresource Technology, 430: 132531.
https://doi.org/10.1016/j.biortech.2025.132531

Guo T., Johnson L., LaBarge G., Penn C., Stumpf R., Baker D., and Shao G., 2020, Less agricultural phosphorus applied in 2019 led to less dissolved phosphorus transported to lake Erie, Environmental Science and Technology, 55(1): 283-291.
https://doi.org/10.1021/acs.est.0c03495

Hao J., Li X., Ju P., and Pasek M., 2025, Active redox cycling of phosphorus on the early Earth, Nature Communications, 16(1): 4596.
https://doi.org/10.1038/s41467-025-60054-3

Hayat S., Li P., Menhas S., Liu W., and Hayat K., 2025, Exploring the nutrient nexus in environmental systems: nitrogen and phosphorus cycling removal recovery and management, Environmental Research, 2025: 122162.
https://doi.org/10.1016/j.envres.2025.122162

Hu J., Zhao Q., Zeng P., Tang Q., Sun Q., and Yin H., 2025, Warming accelerated phosphorus release from the sediment of Lake Chaohu during the decomposition of algal residues: a simulative study, PLOS ONE, 20: e0314534.
https://doi.org/10.1371/journal.pone.0314534

Huang W.Z., and Han Y.P., 2025, Habitat degradation and restoration in aquatic ecosystems: implications for fish populations, International Journal of Aquaculture, 15(4): 175-183.
https://doi.org/10.5376/ija.2025.15.0017

Jin H., Zhang C., Meng S., Wang Q., Ding X., Meng L., Zhuang Y., Yao X., Gao Y., Shi F., Mock T., and Gao H., 2024, Atmospheric deposition and river runoff stimulate the utilization of dissolved organic phosphorus in coastal seas, Nature Communications, 15: 44838.
https://doi.org/10.1038/s41467-024-44838-7

Lin S., 2023, Phosphate limitation and ocean acidification co-shape phytoplankton physiology and community structure, Nature Communications, 14: 38381.
https://doi.org/10.1038/s41467-023-38381-0

Liu D., Li X., Zhang Y., Qiao Q., and Bai L., 2023, Using a multi-isotope approach and isotope mixing models to trace and quantify phosphorus sources in the Tuojiang River Southwest China, Environmental Science and Technology, 57(19): 7328-7335.
https://doi.org/10.1021/acs.est.2c07216

Mi L., Xie Z., Xu W., Waniek J., Pohlmann T., and Mi W., 2023, Air-sea exchange and atmospheric deposition of phthalate esters in the South China Sea, Environmental Science and Technology, 57: 11195-11205.
https://doi.org/10.1021/acs.est.2c09426

Murphy A., Scanlan D., Chen Y., Adams N., Cadman., W., Bottrill A., Bending G., Hammond J., Hitchcock A., Wellington E., and Lidbury I., 2021, Transporter characterisation reveals aminoethylphosphonate mineralisation as a key step in the marine phosphorus redox cycle, Nature Communications, 12(1): 4554.
https://doi.org/10.1038/s41467-021-24646-z

Paerl H., Otten T., and Kudela R., 2018, Mitigating the expansion of harmful algal blooms across the freshwater-to-marine continuum, Environmental Science and Technology, 52(10): 5519-5529.
https://doi.org/10.1021/acs.est.7b05950

Randolph-Flagg N., Ely T., Som S., Shock E., German C., and Hoehler T., 2023, Phosphate availability and implications for life on ocean worlds, Nature Communications, 14: 37770.
https://doi.org/10.1038/s41467-023-37770-9

Trombetta T., Vidussi F., Mas S., Parin D., Simier M., and Mostajir B., 2019, Water temperature drives phytoplankton blooms in coastal waters, PLoS ONE, 14(4): e0214933.
https://doi.org/10.1371/journal.pone.0214933

Wang Y., Ouyang W., Lin C., Zhu W., Critto A., Tysklind M., Wang X., He M., Wang B., and Wu H., 2021, Higher fine particle fraction in sediment increased phosphorus flux to estuary in restored Yellow River basin, Environmental Science and Technology, 55(12): 8081-8091.
https://doi.org/10.1021/acs.est.1c00135

Wang L.T., 2025, From phytoplankton to fish: exploring the trophic levels of aquatic ecosystems, International Journal of Aquaculture, 15(2): 57-66.
https://doi.org/10.5376/ija.2025.15.0007

Wu Q., Guo L., Li X., and Wang Y., 2021, Effect of phosphorus concentration and light/dark condition on phosphorus uptake and distribution with microalgae, Bioresource Technology, 340: 125745.
https://doi.org/10.1016/j.biortech.2021.125745

Xiao X., Agustí S., Pan Y., Yu Y., Li K., Wu J., and Duarte C., 2019, Warming amplifies the frequency of harmful algal blooms with eutrophication in Chinese coastal waters, Environmental Science and Technology, 53(23): 13031-13041.
https://doi.org/10.1021/acs.est.9b03726

Yan Q., Jia Z., Song J., Zhou J., and Cai Z., 2022, Oyster culture changed the phosphorus speciation in sediments through biodeposition, Environmental Research, 214: 114586.
https://doi.org/10.1016/j.envres.2022.114586

Yuan Z., Jiang S., Sheng H., Liu X., Hua H., Liu X., and Zhang Y., 2018, Human perturbation of the global phosphorus cycle: changes and consequences, Environmental Science and Technology, 52(5): 2438-2450.
https://doi.org/10.1021/acs.est.7b03910

Zeng J., Tu Q., Yu X., Qian L., Wang C., Shu L., Liu F., Liu S., Huang Z., He J., Yan Q., and He Z., 2022, PCycDB: a comprehensive and accurate database for fast analysis of phosphorus cycling genes, Microbiome, 10: 83.
https://doi.org/10.1186/s40168-022-01292-1

Zhang C., He Y., Wang J., Chen T., Baltar F., Hu M., Liao J., Xiao X., Li Z., and Dong X., 2025, LucaPCycle: Illuminating microbial phosphorus cycling in deep-sea cold seep sediments using protein language models, Nature Communications, 16: 5413.
https://doi.org/10.1038/s41467-025-60142-4

Zhang F., Wen Z., Wang S., Tang W., Luo Y., Kranz S., Hong H., and Shi D., 2022, Phosphate limitation intensifies negative effects of ocean acidification on globally important nitrogen fixing cyanobacterium, Nature Communications, 13: 6761.
https://doi.org/10.1038/s41467-022-34586-x

Zhao M., Zhang S., Tarhan L., Reinhard C., and Planavsky N., 2020, The role of calcium in regulating marine phosphorus burial and atmospheric oxygenation, Nature Communications, 11: 1919.
https://doi.org/10.1038/s41467-020-15673-3

Zhou J., Li D., Zhao Z., and Huang Y., 2021, Phosphorus bioavailability and the diversity of microbial community in sediment in response to modified calcium peroxide ceramsite capping, Environmental Research, 194: 110682.
https://doi.org/10.1016/j.envres.2020.110682

Zhou Z., Liu Y., Wang S., Xiao J., Cao X., Zhou Y., and Song C., 2023, Interactions between phosphorus enrichment and nitrification accelerate relative nitrogen deficiency during cyanobacterial blooms in a large shallow eutrophic lake, Environmental Science and Technology, 57(6): 2263-2274.
https://doi.org/10.1021/acs.est.2c07599