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Ideas and perspectives: Tipping into the unknown—the global consequences of biogeochemical system collapse

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Abstract

With Earth's tipping points being approached and already exceeded, human-driven disruptions of carbon (C), nitrogen (N), and phosphorus (P) cycles are forcing Earth's biogeochemical systems toward irreversible collapse. Potential functional extinction of key regulatory processes—such as carbonate precipitation, denitrification, phosphorus burial, and methane oxidation—could lead to cascading failures, spread beyond biogeochemical domains and further contribute to destabilize planetary homeostasis. This study examines scenarios how these disruptions may interact across biogeochemical cycles, and how they might create reinforcing feedback loops that

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amplify climate change, accelerate ecosystem degradation, and alter atmospheric and oceanic chemistry.

Our scenarios envision carbon cycle disruptions (ocean acidification, soil carbon loss) weaken CO_2/CH_4 sequestration and boost emissions. Eutrophication and oxygen depletion threaten the nitrogen cycle, increasing nitrates and N_2O. Meanwhile, phosphorus release from hypoxic sediments sustains eutrophication and intensifies greenhouse gas emissions. Changing feedback loops may prevent the recovery of desirable biogeochemical conditions. A shift to anaerobic metabolism would favor sulfate reduction, methanogenesis, and ammonification, triggering biodiversity collapse, expanding anoxic zones, and allowing microbial extremophiles to dominate—echoing early anoxic Earth.

The loss of these regulatory functions would exacerbate global warming and push Earth's ecosystems irreversibly into a "Hothouse Earth" regime. Immediate governance action is necessary to mitigate these risks by managing nutrient cycles, protecting carbon sinks, and incorporating biogeochemical feedbacks into climate policies. Without intervention, the accelerating extinction of key biogeochemical processes may render long-term climate protection unattainable.

Keywords: biogeochemical cycles, functional extinction, feedback loops, climate change, tipping points, ecosystem collapse, planetary boundaries, resilience.

1. Introduction

Human domination of the biophysical environment in an accelerating Anthropocene is moving Planet Earth dangerously towards and beyond global tipping elements (Richardson et al. 2023). Global environmental change has surpassed planetary boundaries, entering a high-risk period for humanity (IPCC, 2018). For instance, land system alterations, ocean acidification and freshwater eutrophication are escalating and nearing critical thresholds (Steffen et al. 20015).

Biogeochemical cycles are not exempt from rapid environmental change. Unprecedented human alterations of the environment fundamentally alter the carbon (C), nitrogen (N), and phosphorus (P) cycles, disrupting biogeochemical fluxes, and

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threatening functional key regulatory processes (Galloway et al. 2008). The loss of these processes could push ecosystems beyond critical thresholds, triggering cascading effects (Rocha et al. 2018) and moving Earth into an irreversible Hothouse Earth regime (Steffen et al. 2018). Once such a shift has occurred the current Holocene climate regime will be elusive. Under such a globally novel Earth systems regime, extinction and fundamental reorganization of microbial pathways, mineralization reactions, and nutrient transformation processes may amplify positive feedback loops, and bolster run-away climate change, ecosystem degradation, biodiversity loss and global biogeochemical disruptions (Falkowski et al., 2000).

Among the most vulnerable processes are carbonate precipitation and burial (Ridgwell and & Zeebe, 2005), which regulate long-term carbon sequestration in the oceans (Berner, 2004); denitrification and anammox, essential for balancing reactive nitrogen levels (Thamdrup & Dalsgaard, 2002); and phosphorus occlusion and burial, which prevent eutrophication and limit primary production (Ruttenberg, 2003). Their substantial alteration would destabilize local ecosystems and amplify planetary-scale feedback loops that climate change. As these disruptions approach critical thresholds, they may trigger tipping points beyond which recovery becomes improbable, leading to irreversible shifts in the Earth system.

In this perspective, we project evidence-based state-of-the-art research into and build speculative but potentially realistic worst-case scenarios about the consequences of the potential collapse of biogeochemical processes. Such an assumption is partly motivated by the current climate trajectory pointing to a global temperature increase exceeding 2°C which would bring severe, widespread impacts (IPCC, 2022). Specifically, we evaluate the mechanisms driving the decline, interactions, and cascading effects on climate regulation and ecosystem stability across altered C, N, and P cycles. Through a global feedback loop perspective, we assess how these disruptions could reinforce one another. Substantial local, regional, and global alterations of interrelated biogeochemical processes may contribute unexpectedly to pushing our Earth toward a fundamentally different and less hospitable regime. The scope and complexity of potential biogeochemical collapse prevent our analysis from being exhaustive; however, our paper's broad yet realistic tendencies justify an urgent call for governance and management action.

We acknowledge upfront that the scenarios presented are alarmist, speculative and lack quantifiable precision. However, the article's primary aim is to emphasize the urgency of addressing critical biogeochemical disruptions, recognizing that quantifiable evidence and a focus on human capacity to adapt and transform may prevent these scenarios from becoming real. Recognizing the potential for system resilience and human innovation is essential, as these should complement, not detract from, the urgent need for a global, coordinated response to prevent irreversible damage (Rockström et al., 2009). The emphasis on immediate action aligns with the principle that preparing for dire possibilities is preferable to being caught unprepared (Taleb, 2007).

2. Functional extinction of carbon processes: from sequestration to atmospheric release

The carbon cycle is experiencing irreversible shifts as sequestration pathways decline and emission routes intensify. Ocean acidification, driven by CO_2 absorption, suppresses carbonate precipitation, essential for long-term carbon burial (Table 1). As pH declines, calcifying organisms (e.g., corals, foraminifera, coccolithophores) struggle to form calcium carbonate, reducing marine carbon storage and weakening the ocean's role as a CO_2 sink, accelerating atmospheric carbon accumulation in a self-reinforcing loop (Feely et al., 2004; Orr et al., 2005).

Rising temperatures and microbial priming effects on land (the stimulation of soil microbial activity by fresh organic inputs, which accelerates the decomposition of older, stable carbon pools) are shifting soils from carbon sinks to sources. While CO_2 fertilization temporarily enhances photosynthesis, warming accelerates organic matter decomposition, outpacing sequestration (Davidson & Janssens, 2006). The functional extinction of slow humification pathways, which stabilize carbon in long-term pools, would deplete soil carbon stocks, intensifying CO_2 emissions and increasing ecosystem desertification (Cotrufo et al.,2019). Simultaneously, permafrost thaw is mobilizing vast reservoirs of ancient organic carbon, fueling microbial decomposition and releasing both CO_2 and methane (Schuur et al., 2015; Turetsky et al., 2020). The rapid destabilization of these frozen carbon stocks represents a tipping point beyond which permafrost ecosystems could shift from a long-term sink to a sustained source of atmospheric carbon. In addition to the above, the forest C pool is threatened by the increment of temperatures and reduction of precipitation, because the severe wildfires

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have increased in forest ecosystems with low fire frequency as boreal and humid-temperate forests (IPCC, 2019). These dynamics may be beyond human control and must be mitigated by global human action.

The shift from methanotrophic mechanisms to unchecked methanogenesis in wetlands could mark an approaching critical tipping point. As warming intensifies, prolonged waterlogging and oxygen depletion lead to the collapse of aerobic methanotrophic communities, reducing methane oxidation capacity (Bange et al., 2010). Although anaerobic oxidation of methane (AOM) via sulfate or nitrate reduction can act as an alternative sink, its efficiency depends on the availability of these electron acceptors, which may be limited in freshwater wetlands and eutrophic systems (Raghoebarsing et al., 2006; Ettwig et al., 2010). Competition for sulfates and nitrates can further favor methanogenesis over AOM in highly anoxic conditions, exacerbating methane accumulation. Since methane has 25 times the warming potential of CO_2 (Myhre et al., 2013), this shift reinforces run-away climate warming and ecosystem degradation.

3. Nitrogen cycle disruptions: the extinction of denitrification and the rise of nitrous oxide

Human-driven nitrogen inputs, particularly fertilizer overuse, are disrupting microbial nitrogen transformations (Galloway et al., 2008). N fertilizer use has increased around 8-fold in 55 years (between 1961 and 2016) for global crop production (Martinez-Dalmau et al., 2021), which has probably favored the increase in N2O emissions because agriculture has been reported to be responsible for two-thirds of the global emissions of this GHG (Janssens-Maenhout et al., 2017). A critical risk is the functional extinction of denitrification, which converts reactive nitrogen to inert N_2 gas. Under eutrophic and anoxic conditions, denitrifying bacteria are replaced by microbial communities favoring incomplete denitrification, leading to increased nitrous oxide (N_2O) emissions, a greenhouse gas 300 times the warming potential of CO_2 (Davidson, 2009). This shift could exponentially increase N_2O accumulation, further accelerating climate change.

Another vulnerable pathway is anaerobic ammonium oxidation (anammox), essential for nitrogen removal in marine and freshwater systems (Kuypers et al., 2003). This process is highly sensitive to thermal and chemical disruptions; its collapse could cause

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ammonium (NH_4^+) to accumulate in aquatic ecosystems, fueling eutrophication, toxic algal blooms, and oxygen depletion (Jetten et al., 2001). The extinction of nitrifying bacteria due to acidification and eutrophication would create a nitrogen-saturated environment, exacerbating imbalances between nitrogen fixation and removal.

4. Phosphorus cycle breakdown: loss of sedimentary storage and self-reinforcing eutrophication

Phosphorus, a non-renewable nutrient critical for primary production, is undergoing irreversible alterations due to agricultural runoff and climate change (Filippelli, 2008). The extinction of phosphorus precipitation and burial pathways, driven by ocean acidification and anoxic sediment conditions, could permanently alter phosphorus availability (Conley et al., 2009). Under normal conditions, phosphorus binds with iron and calcium in sediments, removing it from biological circulation. However, increasing hypoxia releases stored phosphorus back into the water, perpetuating eutrophication in a positive feedback loop (Elser et al., 2007).

Another collapse scenario is emerging in phosphorus-limited ecosystems: phosphorus depletion in soils due to intensive agriculture and erosion threatens terrestrial primary production (Sternberg et al., 2017). In addition, global reserves of phosphate rock may be depleted within 10 years, as several authors estimate that the peak of P fertilizer production will occur around 2030 (Cordell et al., 2009), declining after this year. As phosphorus becomes scarce, plant growth declines, reducing carbon sequestration and compounding climate change while threatening food security and eroding ecosystem resilience.

5. The domino effect: tipping points and cascading extinctions across biogeochemical functions

The simultaneous and interrelated disruption of the C, N, and P cycles initiates multi-layered feedback loops, driving Earth's biogeochemical systems toward and beyond irreversible collapse and novel configurations. The interdependence of these cycles amplifies disturbances, creating a domino effect where the extinction of one biogeochemical function accelerates the degradation of others (Falkowski et al., 2000). Several routes of change can be envisioned:

Collapse of methanotrophic mechanisms: As warming intensifies, oxygen depletion in wetlands, thawing permafrost, and aquatic systems increasingly suppress aerobic methanotrophic processes, reducing methane oxidation capacity and leading to unchecked methane accumulation (Davidson & Janssens, 2006; Bange et al., 2010). While anaerobic methane oxidation (AOM) linked to sulfate and nitrate reduction can provide an alternative sink, its effectiveness is constrained by electron acceptor availability, particularly in freshwater wetlands and eutrophic environments (Raghoebarsing et al., 2006; Ettwig et al., 2010). In highly anoxic conditions, sulfate and nitrate limitation, coupled with increased organic matter decomposition, further shifts microbial dominance toward methanogenesis, intensifying CH_4 emissions. This feedback loop accelerates warming and enhances soil respiration and permafrost thawing, releasing additional CH_4 and CO_2, reinforcing global climate destabilization.

Denitrification failure: Oxygen depletion disrupts nitrogen removal, causing nitrate overaccumulation and increased N_2O emissions, exacerbating greenhouse warming (IPCC, 2021). Excess nitrate intensifies eutrophication, driving algal blooms and further oxygen loss, reinforcing anoxia and suppressing denitrification. This cycle locks nitrogen in aquatic systems, promoting ammonification and worsening water quality, biodiversity loss, and ecosystem instability (Galloway et al., 2008). As denitrification declines, methanogenesis becomes more dominant, shifting microbial pathways toward methane (CH_4) production, further amplifying global warming. If left unchecked, nitrogen-saturated, hypoxic environments will become permanent greenhouse gas sources, accelerating planetary instability (a state where cascading biogeochemical disruptions drive irreversible climate shifts, ecosystem collapse, and feedback loops that push Earth beyond safe operating conditions).

Phosphorus burial loss: Without effective P removal, eutrophication remains self-sustaining, driving algal blooms and oxygen depletion, suppressing nitrification, and amplifying CH_4 and N_2O emissions. Anoxic sediments release stored phosphorus, perpetuating this cycle indefinitely (Conley et al., 2009; Elser et al., 2007; Spears et al. 2013). As eutrophication worsens, sulfate-reducing bacteria thrive, producing toxic hydrogen sulfide (H_2S) and further degrading biodiversity. If phosphorus burial collapse continues, aquatic systems risk becoming permanently hypoxic or anoxic, locked in a cycle of nutrient saturation, greenhouse gas emissions, and ecosystem failure (i.e., the

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loss of structure and function in the ecosystem; Díaz & Rosenberg, 2008; Rockström et al., 2009; Barnosky et al., 2012), contributing to global warming.

As these feedback compounds, tipping points emerge, beyond which natural recovery mechanisms fail (Scheffer et al., 2012, Hessen et al. 2024). The functional extinction of microbial communities mediating C sequestration, N removal, and P stabilization may drive large-scale regime shifts—from carbon-sequestering forests to grasslands, from oxygen-rich oceans to anoxic dead zones, and from nutrient-cycling wetlands to methane-producing landscapes (Lenton et al., 2008).

These cascading disruptions could irreversibly shift Earth's biogeochemical regime and have cascading effects to impair global biodiversity and social-ecological resilience. The accelerating breakdown of these interconnected processes supports the concern about the emergence of a new planetary Hothouse Earth regime (Steffen et al., 2018). Once flipped into such a regime, recovery to the previous conditions is no longer viable, adaptation becomes obsolete and transformation is the only viable option for navigating the accelerating Anthropocene (Angeler et al. 2020a).

6. A Planetary shift: the consequences of biogeochemical extinction

Suppose the regulatory processes of the carbon, nitrogen, and phosphorus cycles collapse. Earth will undergo a fundamental transition toward a drastically altered biosphere (Fig.1). The loss of carbonate precipitation, denitrification, phosphorus burial, and methane oxidation would not only amplify greenhouse gas accumulation but also trigger systemic shifts in atmospheric composition, ocean chemistry, and ecosystem function. As a result, the planet would enter a new equilibrium dominated by anaerobic metabolism, extreme biogeochemical imbalances, and widespread ecological degradation (Fig. 1).

6.1. The decline of habitability: from biosphere to chemosphere

The extinction of biogeochemical processes responsible for climate regulation would drive a significant decline in Earth's habitability (Fig. 1a). Without effective CO_2 sequestration via carbonate precipitation and terrestrial carbon storage, atmospheric C concentrations would continue rising indefinitely, intensifying global warming beyond current worst-case projections (Feely et al., 2004; Orr et al., 2005). Wetlands,

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permafrost, and coastal sediments—historically net carbon sinks—would become permanent methane sources, further compounding the greenhouse effect (Davidson & Janssens, 2006; Bange et al., 2010). Rising temperatures and feedback-driven permafrost thawing would release vast amounts of stored C (primarily as CH_4), accelerating global aridification and heat stress (Lenton et al., 2008; Fig. 1a).

Simultaneously, oceanic oxygen depletion would expand beyond coastal dead zones, reducing habitable marine environments (Rabalais et al., 2010). The loss of denitrification and anammox would lock reactive nitrogen into aquatic systems, fueling sustained eutrophication and reinforcing widespread anoxia (Conley et al., 2009). The intensification of oxygen minimum zones (OMZs) in midwater layers, driven by increased organic matter input and nutrient loading, coupled with excess nitrogen and phosphorus, would create conditions favoring sulfate-reducing bacteria, leading to periodic hydrogen sulfide (H_2S) releases—a known driver of mass extinctions in Earth's past (Canfield, 1998; Knoll et al., 2007).

On land, agricultural collapse would result from P depletion and N saturation. Primary production would decline in P-limited regions, leading to soil degradation and widespread desertification (Elser et al., 2007; Sternberg et al., 2017). In N-saturated systems, toxic algal blooms and soil acidification would disrupt terrestrial food webs, further reducing ecosystem resilience and increasing biodiversity loss (Galloway et al., 2008). The combined failure of C sequestration, N removal, and P stabilization would make large areas of the planet inhospitable for higher-order life forms, shifting Earth's surface toward a chemically unstable, hypoxic, and high-CO_2 state.

6.2. A new biogeochemical regime: anaerobic metabolism and microbial dominance

The expansion of anoxic zones, rather than a complete loss of oxygen throughout the ocean, would shift carbon processing toward anaerobic metabolic pathways—particularly sulfate reduction, methanogenesis, and fermentation—reinforcing localized anoxia and greenhouse gas emissions (Schlesinger, 1997; Fig. 1b). Sulfate-reducing bacteria (SRB) would outcompete aerobic decomposers in these oxygen-depleted regions, generating high concentrations of H_2S, which is not only toxic to most metazoans but also exacerbates oxygen depletion through further microbial and chemical interactions (Canfield, 1998; Fig. 1b).

Methanogenic archaea would proliferate in wetlands, anoxic oceans, and thawing permafrost, shifting the C cycle balance toward CH_4 accumulation (Bange et al., 2010). The extinction of aerobic methane-oxidizing bacteria (MOB) would eliminate a key sink for CH_4, further exacerbating warming (Ettwig et al., 2010; Raghoebarsing et al., 2006). In N cycling, the decline of denitrification would favor ammonification, increasing ammonium accumulation (NH_4^+). At the same time, losing anammox would remove a major pathway for N removal from aquatic systems, leading to a chemically reduced, eutrophic environment (Jetten et al., 2001).

As these shifts progress, macroorganisms dependent on oxygen and stable nutrient cycles would face increasing extinction risks. Complex multicellular life, particularly large vertebrates, would struggle to survive in a world dominated by water scarcity, anoxia, GHG buildup, and disrupted primary production. Ecosystem productivity would decline, leading to food web simplification and the collapse of biodiversity hotspots (Steffen et al., 2015). In contrast, microbial extremophiles adapted to anoxic, high-sulfide, and high-methane environments would thrive, forming the dominant biosphere—a shift reminiscent of early Earth conditions before the Great Oxidation Event (Fig. 1b).

6.3. From an oxygen-rich earth to a methane and sulfide-dominated world

Under current conditions, the biosphere is largely regulated by oxygenic photosynthesis, aerobic respiration, and nutrient cycling that, despite local imbalances, maintains large-scale biogeochemical stability (Fig. 1c). These processes maintain atmospheric O_2 levels, drive carbon sequestration, and stabilize N and P fluxes. However, with the collapse of oxygenic biogeochemical functions, the planet would transition into a high-CO_2, high-CH_4, and high-H_2S regime, chemically resembling Earth's Precambrian epochs or situations of past mass extinction events (Knoll et al., 2007; Lenton et al., 2008; Fig. 1c).

Due to nutrient imbalances, ocean acidification, and CO_2 oversaturation, photosynthetic primary producers would face severe limitations, leading to a net decline in ecosystem productivity. Instead, chemosynthetic and anaerobic microbial processes—such as hydrogenotrophic methanogenesis, sulfur-based energy metabolism, and fermentative C cycling—would dominate biogeochemical fluxes (Falkowski et al., 2000). The terrestrial and marine C cycles would become increasingly driven by microbial respiration rather than plant sequestration, fundamentally altering ecosystem structure.

This transition would render large portions of the planet inhospitable to complex life (Fig. 1c). Marine dead zones, initially localized in eutrophic coastal regions, would expand into open oceans, reducing viable habitats for fish, corals, and other marine organisms. On land, desertification and altered precipitation patterns would lead to the contraction of forests and grasslands, further reducing carbon uptake (Davidson & Janssens, 2006). The biosphere would be dominated by microbial communities adapted to extreme environments, similar to the deep-sea hydrothermal vent ecosystems that persist under oxygen-deficient, high-sulfide conditions.

Conclusions: a planetary shift beyond recovery

The escalating disruption of Earth's biogeochemical cycles risks the irreversible extinction of critical regulatory processes, exacerbating global warming, ecosystem collapse, and nutrient imbalances (Fig. 1). The loss of microbial pathways governing methane oxidation, nitrogen transformation, and phosphorus burial threatens to amplify feedback loops that push planetary stability beyond recoverable limits.

The extinction of these known biogeochemical processes would push Earth beyond its current stable regime, leading to a chemically reduced, microbially dominated world with diminished habitability for complex life. The collapse of CO_2 sequestration, N removal, and P stabilization would accelerate global warming, disrupt nutrient cycles, and shift ecosystem function toward anaerobic metabolism. The resulting feedback loops would lock the planet into a high-CO_2, high-CH_4, and low-O_2 equilibrium, where microbial extremophiles outcompete oxygen-dependent life.

Governance and mitigation must go beyond emissions reduction to actively maintain biogeochemical stability. Prioritizing wetland conservation, soil carbon restoration, and nutrient pollution control can delay the collapse of key ecosystem functions, allowing us to gain more time for designing strategies to navigate the Anthropocene for best-possible sustainability. Advancing microbial ecology research, carbon sequestration modeling, and N and P cycles restoration is essential to integrate biogeochemical feedbacks into climate mitigation policies. Without urgent action based on interdisciplinary collaborations across sectors of society that embrace the known and unknown consequences of rapid social-ecological change (Angeler et al. 2020b), the irreversible extinction of biogeochemical processes may accelerate planetary instability, rendering stabilization of the Holocene climate unattainable.

Critics may argue that the scenarios laid out are alarmist or that the evidence lacks quantifiable precision. However, this article intends to highlight the urgency of addressing these critical issues. The development of certain scenarios aims not to overstate risks, but to prepare for potential outcomes that scientific research indicates as plausible. The interconnectedness and complexity of biogeochemical cycles make precise predictions challenging, but this does not diminish the validity of the concerns raised.

Furthermore, we acknowledge the need for governance and policy development to mitigate these risks. While there may be calls for more quantifiable evidence or a stronger emphasis on social and ecological adaptive and transformative capacity (Angeler et al., 2019; Michaels et al., 2025), the primary goal is to raise awareness and prompt action. Recognizing the potential for natural system resilience and human innovation is crucial, and these aspects should complement, not detract from, the urgent call for a global, coordinated response to prevent irreversible damage. The article's emphasis on immediate action and comprehensive understanding aligns with the principle that it's better to prepare for dire possibilities than to be caught unprepared.

Author contribution

SSC: conceptualization, writing - original draft, and visualization. All authors: investigation, supervision, writing - review and editing, and final approval.

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Table 1. Biogeochemical process disruptions under global environmental change: key risks and consequences.

Biogeochemical process	**Main disruptor**	**Potential risk**	**Consequence for global biogeochemistry**
Carbon sequestration in oceans	Ocean acidification due to CO_2 absorption	Reduced efficiency of biological carbon pump	Weakened oceanic carbon sink increasing atmospheric CO_2
Soil carbon storage	Warming-induced microbial decomposition	Decline in humification, leading to faster carbon turnover	Soil carbon instability, amplifying climate feedbacks
Wetland methane cycling	Enhanced methanogenesis due to CO_2 and temperature rise	Loss of aerobic methanotrophy, increasing methane emissions	Higher CH_4 emissions, intensifying global warming
Carbonate precipitation & burial	Lower pH reducing carbonate ion availability	Decreased carbonate formation, reducing oceanic CO_2 buffer	Loss of long-term marine CO_2 sequestration, disrupting ecosystems
Anaerobic respiration pathways	Nutrient loading & climate warming favoring methanogenesis	Shift from denitrification to methanogenesis, enhancing warming	Greater CH_4 and N_2O emissions, accelerating climate change
Methanotrophic processes	Oxygen depletion suppressing methane oxidation	Collapse of methane oxidation, increasing greenhouse gas flux	Methane accumulation in anoxic zones, worsening feedback loops
Nitrification & denitrification	Excess nitrogen inputs disrupting balance	Loss of anammox process, altering nitrogen cycle dynamics	Increased nitrous oxide emissions, intensifying greenhouse effect
Phosphorus precipitation	Eutrophication overwhelming phosphorus sinks	Reduced phosphorus retention, leading to long-term eutrophication	Enhanced eutrophication, creating hypoxic zones and biodiversity loss
Microbial phosphorus solubilization	Nutrient saturation shifting microbial communities	Decreased microbial P cycling, impairing ecosystem productivity	Reduced phosphorus bioavailability, limiting primary production

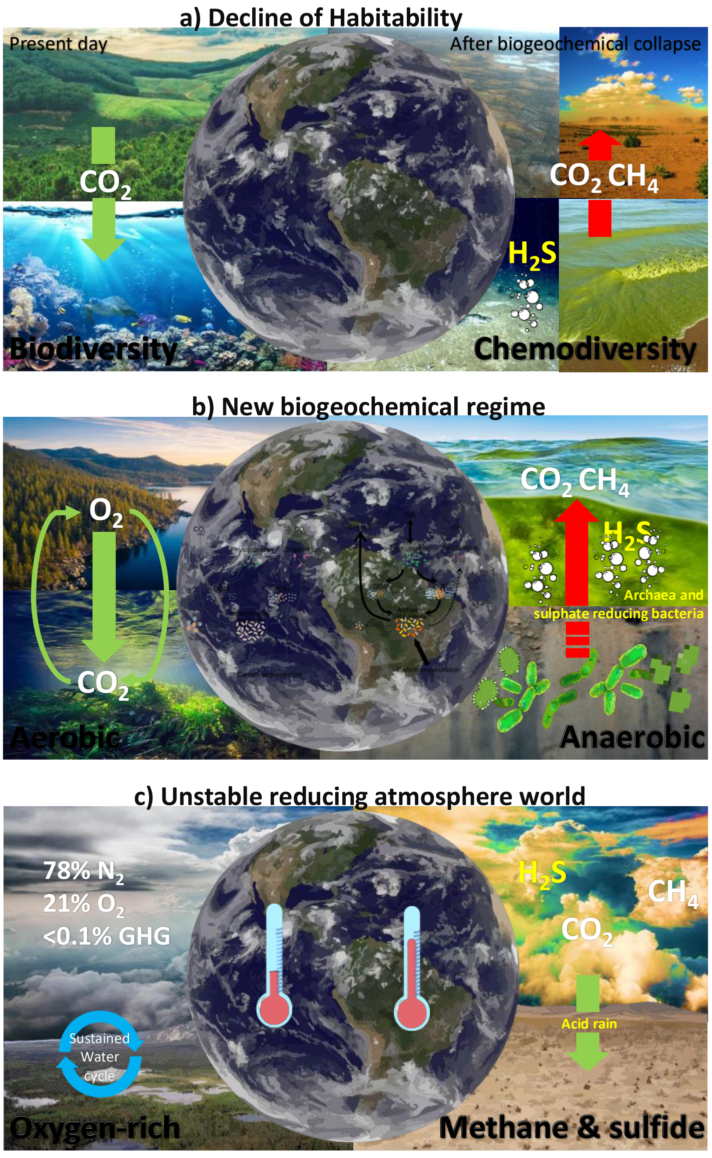

Figure 1. The transition from an Earth regime with desirable biogeochemical functioning to a degraded regime with impaired processes. (a) From a biodiversity-dominated world with oxygenated oceans and stable carbon and nutrient cycles to a chemosphere dominated by methane and sulfide pathways. (b) Future Earth under biogeochemical collapse: anaerobic ocean zones, widespread anoxia, disrupted nutrient cycles, and microbial dominance. (c) Atmospheric shift: from an oxygen-rich atmosphere to a methane- and sulfide-dominated world, leading to extreme climatic instability and ecosystem collapse.