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Carbon Pathogen Dynamics and Carbon Credits: The Invisible Biological Force Shaping Climate Change

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Carbon sequestration has become one of the most important natural approaches for reducing atmospheric carbon dioxide and mitigating climate change. Forests, wetlands, agricultural soils, mangroves, and marine ecosystems act as major carbon sinks by absorbing and storing carbon for long periods. However, recent scientific evidence suggests that pathogens and microbial interactions strongly influence the stability of stored carbon. Disease-causing organisms can weaken plants, accelerate decomposition, alter microbial carbon use efficiency, and increase greenhouse gas emissions. Climate change further intensifies these interactions by increasing environmental stress and expanding pathogen distribution. Researchers collectively highlighted the strong connection between ecosystem health, microbial ecology, biodiversity, and long-term carbon stability. This article discusses the concept of carbon pathogen dynamics, the role of microorganisms in carbon cycling, the impact of disease outbreaks on terrestrial and aquatic ecosystems, and the implications for carbon credit systems. Further, emphasises the need for biodiversity conservation, disease monitoring, and sustainable ecosystem management to ensure reliable climate mitigation.

Keywords: Carbon sequestration, Carbon credits, Pathogen dynamics, Climate change, Microbial ecology, Blue carbon, Sustainable management

Introduction

Climate change has become one of the greatest environmental concerns of the modern world. Increasing greenhouse gas emissions, especially carbon dioxide, are contributing to rising global temperatures, melting glaciers, sea-level rise, biodiversity loss, and extreme climatic events. In response to these challenges, scientists and policymakers are focusing heavily on carbon sequestration and carbon credit systems as major climate mitigation strategies. Natural ecosystems such as forests, agricultural soils, mangroves, wetlands, and marine ecosystems absorb atmospheric carbon dioxide and store it in biomass and sediments. These ecosystems are therefore considered major carbon sinks capable of slowing global warming. However, recent ecological studies indicate that the biological stability of these ecosystems is strongly influenced by pathogens and microbial processes.

Microorganisms regulate decomposition, nutrient cycling, soil fertility, and carbon transformation, while pathogens can damage vegetation, reduce productivity, and accelerate carbon release into the atmosphere. Allen et al. (2010) demonstrated that climate-induced stress contributes significantly to forest mortality worldwide, while Harvell et al. (2019) observed that marine disease outbreaks associated with warming oceans destabilise coastal ecosystems. Similarly, Anderegg et al. (2020) reported that climate-driven disturbances threaten the long-term climate mitigation potential of forests.

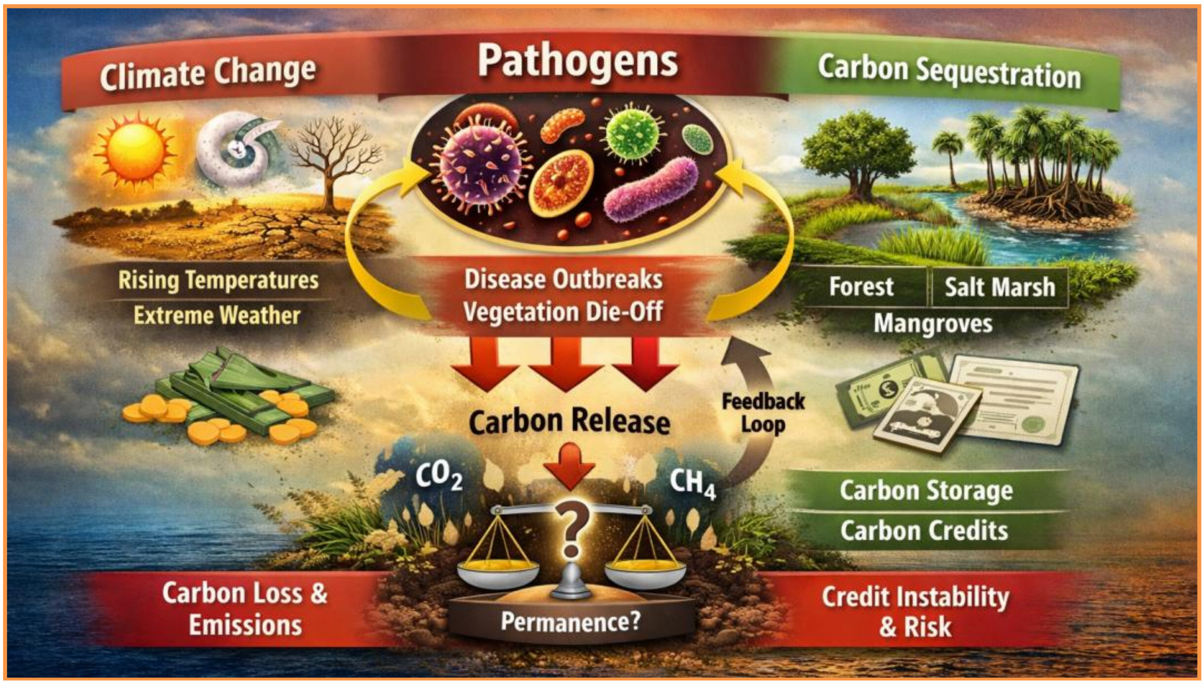

Fig. Interaction Between Climate Change, Pathogen Dynamics, Carbon Sequestration, and Carbon Credit Stability

Carbon credit systems also depend on the assumption that ecosystems will continue storing carbon for long periods. However, disease outbreaks caused by fungi, bacteria, insects, and viruses may rapidly reverse years of carbon accumulation. Badgley et al. (2022) and Haya et al. (2020) warned that ecological disturbances are often underestimated in carbon accounting systems. This explains the emerging concept of carbon-pathogen dynamics and discusses how microbial interactions and disease outbreaks influence carbon sequestration, ecosystem resilience, and carbon credit reliability.

Carbon-Pathogen Dynamics and Carbon Cycling

Carbon-pathogen dynamics refers to the interaction between carbon cycling processes and disease-causing organisms within ecosystems. Carbon is continuously exchanged between the atmosphere, plants, soil, water, and microorganisms through photosynthesis, respiration, decomposition, and microbial metabolism. Plants absorb atmospheric carbon dioxide during photosynthesis and convert it into organic compounds that support growth and ecosystem productivity. However, pathogens depend on these carbon resources for survival and reproduction. When pathogens infect plants or aquatic vegetation, carbon allocation changes significantly. Cotrufo et al. (2013) stated that microbial processes determine whether carbon becomes stabilised in soils or released into the atmosphere. Disease outbreaks redirect carbon from plant growth towards defence and repair mechanisms. In severe infections, vegetation dies, increasing decomposition and atmospheric carbon emissions.

According to Schimel and Schaeffer (2012) described decomposition as a major microbial pathway controlling carbon release. Trumbore et al. (2015) demonstrated that disease outbreaks can rapidly transform carbon sinks into carbon sources. Climate change intensifies these interactions. Rising temperatures, droughts, floods, and environmental stress weaken ecosystem resistance and favour pathogen spread. Kurz et al. (2008) documented how mountain pine beetle outbreaks in North America caused extensive forest mortality and large-scale carbon release. Thus, carbon sequestration is not only a physical storage process but also a biologically regulated system strongly influenced by microbial ecology and disease dynamics.

Role of Microorganisms in Carbon Sequestration

Microorganisms are among the most important regulators of the global carbon cycle. Bacteria, fungi, algae, archaea, and viruses influence carbon storage, decomposition, nutrient cycling, and ecosystem productivity. Falkowski et al. (2008) described microorganisms as the “engines” of Earth’s biogeochemical cycles. Photosynthetic microorganisms such as phytoplankton and cyanobacteria absorb enormous amounts of atmospheric carbon dioxide and contribute to long-term carbon burial in marine sediments. At the same time, heterotrophic microbes decompose dead organic matter and release carbon dioxide through respiration. Allison et al. (2010) reported that rising temperatures increase microbial activity and accelerate soil carbon decomposition.

Pathogenic microorganisms differ from beneficial microbes because they exploit living hosts. Mordecai (2011) explained that pathogens suppress plant productivity, alter species composition, and reduce ecosystem resilience. In contrast, beneficial microbial communities improve nutrient cycling and disease suppression. Van der Heijden et al. (2008) emphasised that healthy and diverse soil microbial communities support sustainable carbon sequestration. Similarly, Manzoni et al. (2012) highlighted the importance of microbial carbon use efficiency, which determines whether carbon is stored in microbial biomass or released into the atmosphere. When pathogens dominate ecosystems, microbial efficiency decreases and carbon losses increase. Therefore, maintaining microbial diversity and ecological balance is essential for long-term carbon stability.

Forests, Blue Carbon Ecosystems, and Disease Outbreaks

Forests are among the largest terrestrial carbon sinks on Earth. Trees store carbon within trunks, branches, leaves, roots, and soils. However, forests worldwide are increasingly threatened by disease outbreaks, invasive pathogens, drought, and climate stress. Allen et al. (2010) documented widespread heat and drought-induced forest mortality across several continents. Similarly, Desprez-Loustau et al. (2006) explained that drought weakens tree defence systems and increases vulnerability to fungal pathogens and insect attacks. One major example is the mountain pine beetle outbreak described by Kurz et al. (2008), where warming temperatures enabled beetle populations to expand rapidly, killing millions of hectares of forests and releasing large amounts of stored carbon.

Blue carbon ecosystems such as mangroves, seagrass meadows, and salt marshes are also extremely important carbon sinks. McLeod et al. (2011) stated that coastal wetlands can store carbon for centuries within waterlogged sediments. However, these ecosystems are highly vulnerable to disease outbreaks and climate stress. Sullivan et al. (2018) reported severe seagrass mortality caused by pathogenic Labyrinthula species in Australia. Harvell et al. (2019) observed that marine heatwaves and diseases contribute to large-scale ecosystem collapse.

Disease outbreaks in blue carbon ecosystems reduce photosynthetic carbon uptake, destabilise sediments, and increase decomposition. Pendleton et al. (2012) estimated that degradation of coastal vegetated ecosystems contributes significantly to global greenhouse gas emissions. These findings demonstrate that protecting ecosystem health is essential for maintaining long-term carbon sequestration.

Carbon Credits and Ecosystem Health

Carbon credits represent one metric tonne of carbon dioxide removed or avoided from the atmosphere. Nature-based carbon credits are generated through projects involving forests, agricultural soils, mangroves, and wetlands. The success of carbon credit systems depends heavily on permanence, meaning that stored carbon must remain stable over long periods. However, disease outbreaks and ecological disturbances threaten this permanence. Badgley et al. (2022) identified over-crediting problems within some forest carbon offset programs, suggesting that ecological risks are often underestimated. Haya et al. (2020) further explained that uncertainty management remains a major challenge in carbon markets.

Pathogens can rapidly reverse years of carbon accumulation. A forest restored for carbon credits may lose large amounts of biomass during disease outbreaks or climate stress events. Similarly, blue carbon ecosystems may collapse due to warming oceans, pollution, or microbial infections. Despite these risks, many carbon accounting systems still focus mainly on physical carbon measurements while neglecting ecosystem health indicators. Researchers increasingly argue that biodiversity, microbial diversity, and disease resistance should become essential components of carbon credit certification systems. Integrating ecological health into carbon finance would improve both environmental integrity and market reliability.

Biodiversity Monitoring and Future Strategies

Biodiversity plays a crucial role in suppressing pathogens and stabilising ecosystems. Keesing et al. (2010) explained that diverse ecosystems often experience lower disease transmission because ecological interactions suppress pathogen dominance. In forests and agricultural systems, diverse microbial communities improve soil fertility and disease resistance. Van der Heijden et al. (2015) highlighted the importance of beneficial fungi and microbes in supporting ecosystem productivity.

Modern technologies are also improving disease monitoring in carbon sequestration projects. Environmental DNA (eDNA), metagenomics, remote sensing, and artificial intelligence can help identify early signs of ecosystem stress and pathogen outbreaks. Future climate mitigation strategies must therefore integrate ecology, microbiology, biodiversity conservation, and adaptive carbon management. Mixed-species plantations, organic soil management, restoration of native vegetation, and improved microbial health can strengthen ecosystem resilience and improve long-term carbon storage. Nature-based solutions should prioritise ecosystem integrity rather than carbon quantity alone because healthy ecosystems provide climate regulation, biodiversity conservation, water purification, and disease suppression simultaneously.

Conclusion

Carbon pathogen dynamics are an important but often neglected part of climate change and carbon sequestration. Pathogens affect decomposition, microbial activity, biodiversity, and the long-term storage of carbon in both terrestrial and aquatic ecosystems. The disease outbreaks can quickly reduce stored carbon and weaken the reliability of carbon credit systems. Climate change further increases these risks by creating environmental stress and encouraging the spread of pathogens. Therefore, future climate strategies should focus not only on carbon storage but also on ecosystem health, biodiversity conservation, microbial stability, and sustainable management practices to ensure long-term environmental resilience.

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