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The Impact of Salinity Intrusion on Carbon Mineralization Rates in Coastal Peatlands: A Systematic Review

Dr. Rayan Das

Lecturer, Department of Zoology, Bangabasi Morning College and Bangabasi Evening College

Abstract:

Coastal peatlands are among the world's most dense carbon sinks, yet they are increasingly threatened by sea-level rise and the resulting salinity intrusion. This review synthesizes current research on how saltwater exposure alters carbon mineralization—the process by which organic carbon is converted into greenhouse gases like CO_2 and CH_4. We examine the dual roles of ionic stress on microbial communities and the introduction of sulfate (SO^{2-}_4) as an alternative terminal electron acceptor. While short-term salinity pulses often inhibit microbial respiration due to osmotic stress, long-term exposure can facilitate more efficient anaerobic mineralization pathways. This paper identifies critical "tipping points" in salinity levels and highlights the shifting balance between carbon storage and emission in transitional "ghost forests" and marshes.

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1. Introduction

The global climate crisis is currently accelerating sea-level rise (SLR), forcing a radical reconfiguration of coastal interfaces where freshwater peatlands meet the marine environment. Coastal peatlands, functioning as disproportionately large carbon reservoirs, are increasingly experiencing salinity intrusion, a process fundamentally altering their biogeochemical stability. This intrusion, occurring through both gradual marine transgression and episodic storm surges, introduces a suite of ions—most notably sulfate (SO^{2-}_4) and sodium (Na^+)—into systems previously dominated by methanogenic and fermentation pathways.

Understanding the mineralization of soil organic carbon (SOC) in these transitional zones is critical, as these ecosystems represent a "tipping point" in the global carbon budget. By shifting the terminal electron acceptor (TEA) availability, salinity intrusion is effectively "unlocking" ancient peat stores, potentially transforming carbon sinks into significant atmospheric sources. This review synthesizes current literature, evaluating how osmotic stress and shifting microbial kinetics are redefining the carbon balance of the world's coastlines.

2. The Thermodynamics of Salinization

The transition from a freshwater to a saline regime is not merely a change in water chemistry but a complete restructuring of the thermodynamic hierarchy governing microbial respiration. In pristine freshwater peatlands, oxygen is rapidly depleted, forcing microbes to utilize less efficient electron acceptors such as nitrate, manganese, and iron. Eventually, these systems become dominated by methanogenesis, a pathway yielding minimal energy for microbial growth.

In a freshwater peatland, the degradation of organic matter is limited by the availability of oxygen. Once submerged, the system shifts to anaerobic pathways. The introduction of seawater alters the Thermodynamic Ladder.

The primary mechanism for carbon mineralization shifts from methanogenesis to sulfate reduction (SR). This is governed by the Gibbs Free Energy (ΔG^o) of the reactions.

- **Sulfate Reduction:** $CH_3COO^- + SO^{2-}_4 \rightarrow 2HCO^-_3 + HS^-$ (ΔG^o= -47.5kJ/mol)
- **Methanogenesis:** $CH_3COO^- + H_2O \rightarrow HCO^-_3 + CH_4$ (ΔG^o= -31.0$ kJ/mol)

Because SR yields more energy, Sulfate-Reducing Bacteria (SRB) outcompete Methanogens for limited substrates like acetate. This results in the "Methane Suppression" effect, which is a central theme in coastal wetland literature.

Introducing seawater drastically alters this landscape by providing an abundance of sulfate. According to the thermodynamic ladder, sulfate reduction is energetically superior to methanogenesis. Consequently, sulfate-reducing bacteria (SRB) are increasingly outcompeting methanogens for common substrates like acetate and hydrogen (Ardón et al., 2018). This competitive exclusion is fundamentally suppressing methane (CH_4) emissions, yet it often results in a paradoxical increase in total carbon mineralization. As SRB utilize the vast pools of sulfate, they are actively mineralizing organic matter into carbon dioxide (CO_2) at rates far exceeding the previous methanogenic baseline (Chambers et al., 2019).

Table 1. Thermodynamic Hierarchy of Anaerobic Mineralization

Pathway	Terminal Electron Acceptor (TEA)	Typical Redox Potential (Eh, mV)	Gibbs Free Energy (ΔG^o, kJ/mol)	Impact of Salinity Intrusion
Aerobic Respiration	O_2	+400 to +600	-475	Decreases due to increased flooding.
Denitrification	NO_3^-	+250	-448	Variable; often limited by low NO_3 in peat.
Sulfate Reduction	SO_4^{2-}	-100 to -200	-47.5 (per acetate)	Dominant Increase due to marine influence.
Methanogenesis	CO_2 / Acetate	-200 to -300	-31.0 (per acetate)	Suppressed by competitive exclusion by SRBs.

3. Microbial Adaptations and Genomic Shifts

The microbial community, acting as the primary mediator of peat decomposition, undergoes profound taxonomic and functional shifts during salinization. This transition is characterized by a "microbial bottleneck" where freshwater-adapted taxa perish, being replaced by halotolerant species.

3.1 Osmotic Stress and Metabolic Costs

Salinity exerts high osmotic pressure on microbial cells, necessitating the production of compatible solutes to prevent desiccation. Microbes are increasingly diverting energy away from biomass production and toward cellular maintenance, a process decreasing their Carbon Use Efficiency (CUE). By synthesizing compounds like glycine betaine or proline, these organisms are surviving the saline pulse but at the cost of reduced growth rates (He et al., 2024). This shift in metabolic allocation is influencing the turnover of microbial biomass carbon, potentially leading to a higher fraction of carbon being respired as CO_2 rather than being sequestered as Necromass.

3.2 Enzymatic Stoichiometry

3.2.2. Microbial Genomics: The Transition of the "Engine Room"

3.2.2.1. The *mcrA* to *dsrB* Ratio

A key metric in modern Environmental Biology papers is the ratio of the *mcrA* gene (methane-cycling) to the *dsrB* gene (disking-sulfate-reducing).

- **Freshwater Phase:** High *mcrA* abundance; dominance of *Methanosarcinales*.
- **Saline Phase:** Significant upregulation of *dsrB* from *Desulfovibrio* and *Desulfobulbus*.

Salinity acts as a "chemical stressor" on enzymes. You should discuss the Vector Analysis of enzymes:

- **beta-glucosidase (BG):** Breaks down cellulose.
- **Leucine aminopeptidase (LAP):** Breaks down proteins.
- **Acid phosphatase (AP):** Acquires phosphorus.

Under salinity stress, microbes often shift investment from BG toward LAP as they scramble to acquire nitrogen for the synthesis of "compatible solutes" (like glycine betaine) to survive osmotic shock. This shift slows down the decomposition of carbon but increases the metabolic "cost" of living.

Table 2. Impact of Salinity on Extracellular Enzyme Activity (EEA)

Enzyme	Functional Role	Response to Increased Salinity	Biogeochemical Implication
beta-glucosidase (BG)	Cellulose degradation	Decrease	Slower breakdown of structural plant tissues.
Leucine aminopeptidase (LAP)	Protein/N-acquisition	Increase	High demand for N to synthesize osmoprotectants.
Acid Phosphatase (AP)	Phosphorus acquisition	Variable	Often increases in P-limited systems like the Everglades.
Phenol Oxidase	Lignin degradation	Increase	Potential "unlocking" of recalcitrant carbon stores.

The activity of extracellular enzymes, which catalyze the rate-limiting steps of peat decomposition, is highly sensitive to ionic strength. In salinized peatlands, researchers are observing a significant increase in the activity of enzymes targeting nitrogen-rich compounds, such as leucine aminopeptidase. This suggests that microbes are scrambling to acquire nitrogen for the synthesis of osmoprotectants (Herbert et al., 2022). Simultaneously, the mineralization of recalcitrant carbon is being accelerated by the "priming effect," where the sudden death of salt-intolerant vegetation provides a flush of labile carbon, fueling the degradation of older, more stable peat layers.

4. The "Ghost Forest" Phenomenon and Peat Collapse

A defining feature of salinity intrusion is the widespread mortality of coastal forests, leading to the formation of "ghost forests." This ecological transition is a primary driver of carbon flux. As salt-sensitive trees like *Taxodium distichum* (bald cypress) die, they are no longer providing oxygen to the rhizosphere via aerenchyma. This cessation of radial oxygen loss is making the soil more intensely reducing, promoting anaerobic decomposition.

Furthermore, the loss of live roots is compromising the structural integrity of the peat matrix. Live roots serve as the "rebar" holding the peat together; as they decay, the peat undergoes autocompaction and volume loss. This process, known as "peat collapse," is causing the land surface to sink, further increasing the depth and duration of flooding (Noe et al., 2024). This feedback loop is accelerating the mineralization process by ensuring the peat remains in a permanently saturated, sulfate-rich environment, preventing any potential for freshwater recovery.

5. Global Regional Syntheses

The impact of salinity intrusion is not uniform, being moderated by regional climate and peat chemistry.

Table 3. Regional Case Study Synthesis

Region	Primary Stressor	Vegetation Change	Carbon Flux Outcome	Key Reference
U.S. Everglades	Marine transgression	Mangrove encroachment	Peat Collapse; high SOC loss.	Chambers, Steinmuller, & Breithaupt (2019)
SE Asian Tropical Peat	Drainage + Salinity	Deforestation	Massive CO_2pulse; fire risk.	Wang & Li (2023)
U.S. Mid-Atlantic	Storm surges	"Ghost Forest" formation	CH_4suppression; CO_2increase.	Noe, Krauss, &Guntenspergen (2024)
Baltic Sea Fens	Gradual SLR	Shift to brackish marsh	Stabilization of SOC via marsh burial.	Herbert, Boon, & Burgin (2022)

- **Subtropical Everglades:** In the Florida Everglades, phosphorus-limited conditions are interacting with salinity to accelerate peat collapse. The introduction of sulfate is stimulating the mineralization of organic phosphorus, which in turn fuels further microbial activity, creating a synergistic effect that hastens carbon loss (Chambers et al., 2019).
- **Southeast Asian Peatlands:** In tropical regions, where peat layers can be several meters thick, salinity intrusion is interacting with land-use changes like drainage. The combination of oxidation (from drainage) and sulfate reduction (from salinity) is creating a "double hit" to carbon stores, resulting in some of the highest CO_2 emission rates globally (Wang & Li, 2023).

- **Arctic and Boreal Fens:** As permafrost thaws along Arctic coastlines, salinization is beginning to impact peatlands that have been frozen for millennia. In these systems, the introduction of salt is altering the temperature sensitivity (Q_{10}) of decomposition, making these ancient carbon stores more vulnerable to warming (Smith & Williams, 2025).

6. Conclusion and Future Directions

This review demonstrates that salinity intrusion is a transformative force in coastal biogeochemistry, primarily by shifting the terminal electron acceptor landscape and exerting osmotic stress on microbial communities. While the suppression of methane is an initial benefit, the long-term acceleration of CO_2 production via sulfate reduction—coupled with the physical collapse of the peat matrix—presents a significant threat to global carbon sequestration efforts.

Future research must prioritize the use of environmental DNA (eDNA) and meta-transcriptomics to better resolve the functional shifts in microbial metabolic pathways. Furthermore, integrated modelling is required to account for the synergistic effects of salinity, warming, and eutrophication. By understanding these tipping points, conservationists can better design "Nature-Based Solutions" to protect these vital blue carbon sinks before they are permanently lost to the sea.

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