

Research Advances on the Influence Mechanisms of Tidal Action and Wet-Dry Alternation on Carbon Exchange in Salt Marsh Wetlands: A Post-print

Authors: Han Guangxuan

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Abstract

Tidal salt marsh wetlands exhibit high carbon accumulation rates and low CH₄ emissions, representing one of the most intensive carbon sinks on Earth. Simultaneously, climate warming and sea level rise may enable salt marsh wetlands to capture and bury atmospheric CO₂ more rapidly; consequently, the “blue carbon” of salt marsh wetlands plays a crucial role in climate change mitigation. The most distinctive feature separating tidal salt marsh wetlands from other wetland types is their periodic inundation and exposure under tidal action, accompanied by alternating wet-dry cycles of salt surface accumulation and leaching, which may constitute a key factor controlling carbon exchange processes and carbon budget equilibrium in salt marsh wetlands. However, the influences of tidal hydrodynamic processes and their periodic wet-dry alternation on the key processes of carbon exchange and carbon sink formation mechanisms in salt marsh wetlands remain inadequately understood. Furthermore, previous studies have typically assessed salt marsh wetland carbon balance by considering vertical CO₂ or CH₄ exchange or lateral fluxes of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic carbon (POC) in isolation, which is clearly inadequate. Therefore, to accurately evaluate and predict the sequestration capacity of blue carbon in salt marsh wetlands, it is essential to systematically investigate the effects of different tidal stages on carbon exchange processes; thoroughly analyze the microbial mechanisms underlying carbon exchange under tidal action; examine the impacts of tidal hydrodynamic forces on the production, release, and export of DOC, DIC, and POC to adjacent water bodies; elucidate the effects of tidal action on carbon sink formation mechanisms; and incorporate tidal hydrodynamic processes as variables to establish carbon cycle models for salt marsh wetlands.

Full Text

Preamble

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Research Progress on the Mechanisms of Tidal Action and Drying-Wetting Cycles Affecting Carbon Exchange in Salt Marshes

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Key Laboratory of Coastal Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences

Abstract

Tidal salt marshes exhibit high carbon accumulation rates and low CH₄ emissions, representing some of the most intensive carbon sinks on Earth. Climate warming and sea level rise may enable salt marshes to capture and bury atmospheric CO₂ more rapidly in the future. Consequently, the “blue carbon” stored in tidal salt marshes plays a crucial role in the global carbon cycle and climate change mitigation. Unlike other wetland types, salt marshes experience periodic flooding and exposure driven by tides, leading to alternating cycles of salt accumulation and leaching. These tidal flooding and associated drying-wetting cycles profoundly impact the carbon biogeochemical cycle and carbon balance in salt marshes. However, the responses of carbon exchange and sequestration to tidal hydrodynamic processes and drying-wetting cycles remain unclear. Previous studies have typically evaluated the carbon budget of tidal salt marshes by considering either vertical CO₂ or CH₄ exchange or lateral fluxes of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic carbon (POC) in isolation, which limits accurate assessment of carbon sequestration processes.

To accurately estimate and predict the blue carbon sequestration capacity of salt marshes, future research must: (1) systematically investigate the effects of different tidal stages on key carbon exchange processes; (2) clarify the microbial mechanisms of carbon exchange under tidal action; (3) explore how tidal hydrodynamics influence the production, release, and leaching of DOC, DIC, and POC from salt marshes to adjacent coastal waters; (4) elucidate the influence of tidal action on carbon sequestration mechanisms; and (5) incorporate tidal hydrodynamic processes as variables into salt marsh carbon cycle models to accurately evaluate their carbon budgets.

Keywords: carbon exchange; salt marsh; tidal action; drying-wetting cycles;

carbon sequestration mechanisms

1. Carbon Exchange Processes and Observation Methods in Salt Marshes

Carbon exchange in salt marshes includes vertical CO_2 exchange and lateral fluxes of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic carbon (POC). Through photosynthesis, plants absorb carbon and synthesize organic matter, representing gross primary production (GPP). Simultaneously, plants consume carbon for maintenance respiration and release CO_2 . Plant litter and soil organic carbon undergo mineralization and decomposition by microorganisms under aerobic conditions, releasing CO_2 . The sum of autotrophic and heterotrophic respiration constitutes ecosystem respiration (Reco). Net ecosystem CO_2 exchange (NEE) represents the balance between GPP and Reco. Wetlands also emit CH_4 to the atmosphere. During flooding, plant residues and soil organic carbon produce CH_4 under anaerobic conditions, which is released via diffusion, ebullition, and plant-mediated transport, though some CH_4 is oxidized by methanotrophs in the rhizosphere and shallow oxidized soil layers.

The carbon source-sink function of salt marshes depends on the net balance between ecosystem carbon uptake and atmospheric emissions. Tides affect vegetation productivity and soil organic carbon formation and decomposition through tidal flooding and drying-wetting cycles, while sediment supply directly influences intertidal wetland carbon sequestration capacity. Tides also indirectly affect these processes by altering nutrient availability, salinity, and redox potential. As transitional ecosystems between terrestrial and marine environments, tidal salt marshes can export soil organic carbon as DOC, DIC, and POC to adjacent water bodies through marine tides and surface runoff. This lateral carbon migration and export represents a major pathway for soil carbon loss via hydrological processes and plays a significant role in salt marsh carbon cycling [15-16]. Therefore, accurate assessment of salt marsh carbon source-sink functions requires simultaneous consideration of both vertical and lateral carbon exchange processes [Figure 1: see original paper].

Researchers primarily use eddy covariance and chamber methods to measure salt marsh CO_2 exchange, combined with field sampling and laboratory analysis to determine DOC, DIC, and POC concentrations and fluxes. Advances in eddy covariance technology provide new approaches for investigating spatiotemporal variations in ecosystem-scale CO_2 exchange and have become the most reliable method for long-term carbon flux measurement [17]. This technique is considered the standard for directly measuring material and energy exchange fluxes between terrestrial ecosystems and the atmosphere. Studies have been conducted in various locations including the Texas Gulf Coast [18], Virginia's eastern shore [19], the Everglades [20], southwestern French intertidal mudflats [21], and Chinese estuaries such as the Yangtze River [22], Yellow River [10,23], Min River [24-25], Liao River [26], and Zhangjiang River in Fujian.

Current CH_4 emission observations in salt marshes rely mainly on chamber methods [24-25,27]. Traditional chamber measurements require manual operation, limiting long-term continuous automatic monitoring. Although improved automated chamber systems exist, their low temporal resolution hampers capture of complete tidal effects on CO_2 exchange, and spatial heterogeneity complicates upscaling [28]. In contrast, eddy covariance provides larger spatial coverage, longer duration, and higher temporal resolution, enabling quantification of tidal and drying-wetting effects at the ecosystem scale and facilitating accurate assessment of salt marsh carbon sink functions.

2. Effects of Tidal Action and Drying-Wetting Cycles on Marsh-Atmosphere Carbon Exchange

The primary distinction between tidal salt marshes and other wetlands is that tides affect not only water levels but also create distinctive flooding and exposure cycles [29]. Tidal flooding and ebbing influence vegetation photosynthesis and respiration, and consequently CO_2 exchange, by altering oxygen availability, diffusion rates, and microbial activity [20,30]. Tidal inundation reduces effective leaf area for photosynthesis [17] and decreases maximum daytime photosynthetic rates [10]. Ecosystem CO_2 emissions are lowest during flooding compared to pre-flood and post-ebb periods [24]. Tidal flooding significantly reduces CO_2 flux from salt marshes to the atmosphere, with emission rates negatively correlated with tidal height and proportional to flooding depth and duration [29,30]. As intertidal flooding varies with tides, CO_2 exchange exhibits periodic patterns synchronized with or slightly lagging tidal cycles, with brief but intense effects [22,30].

Tidal seawater intrusion introduces sulfate-rich electron acceptors that shift methanogenesis to sulfate reduction, reducing CH_4 emissions [25,31]. During flooding, soils may not become fully anaerobic, and surface water fluctuations can dissolve atmospheric oxygen, promoting CH_4 oxidation alongside production [31-32]. While tidal flooding provides anaerobic conditions for CH_4 production, elevated water levels may not necessarily increase emissions due to constraints on substrate availability and altered photosynthesis. CH_4 fluxes during flooding are typically lower than pre-flood and post-ebb periods [24], with slack tide emissions lower than during flood and ebb phases [32]. Periodic tidal action sufficiently disrupts marsh environments to affect CH_4 release [25,32].

Tidal drying-wetting cycles represent the most common natural process in salt marshes [33-34], subjecting soils to physical, chemical, and biological transformations between dry and wet states. These cycles profoundly affect CO_2 absorption, CH_4 production, and transport processes through several mechanisms: (1) Soil shrinkage and swelling disrupt physical aggregates, affecting structure, porosity, and aeration, which influences anaerobic and aerobic processes at the soil-atmosphere interface. High soil moisture during spring tides inhibits O_2 diffusion while rapidly depleting existing O_2 , causing redox potential (Eh) to decline [35-36]. (2) Drying-wetting cycles cause salinity fluctuations through sur-

face salt accumulation during exposure and leaching during inundation, creating characteristic salinity gradients [33]. Elevated salinity can inhibit microbial activity through osmotic stress, reducing organic matter decomposition rates [37], with CH_4 release negatively correlated with salinity [38-39]. High salinity also causes plant water loss, reducing photosynthesis and primary productivity [18], while ecosystem respiration coupled with plant activity decreases with increasing salinity [40]. (3) Drying reduces soil water potential, causing microbial cell rupture and death through osmotic shock [41]. Rewetting alters microbial osmotic pressure, potentially lysing cells or causing solute leakage [42]. Drying-wetting transitions shift microbial communities from aerobic to anaerobic dominance, dramatically stimulating activity and causing rapid, pulsed CO_2 release [43-45]. These “Birch effects” from drying-wetting cycles are key processes for carbon greenhouse gas release [45]. (4) Drying-wetting cycles affect plant physiological processes like photosynthesis and protein synthesis by altering soil moisture and salinity [12]. High salinity from prolonged exposure represents a unique environmental factor in intertidal wetlands that shapes plant distribution and productivity [18].

3. Effects of Tidal Action and Drying-Wetting Cycles on Marsh-Water Carbon Exchange

As transitional ecosystems, lateral carbon fluxes of DOC, DIC, and POC in salt marshes constitute important components of carbon budgets [47-48]. These fluxes originate from plant litter leaching and sediment carbon release. For example, Ontario’s coastal wetlands export $(1.5 \pm 0.7) \text{gCm}^{-2} \text{d}^{-1}$ of DOC [51], while U.S. coastal wetlands export $(8.3 \pm 3.7) \text{gCm}^{-2} \text{d}^{-1}$ [47], an order of magnitude greater than freshwater wetlands. Soil microorganisms transform organic carbon into DIC, which exchanges with adjacent waters through runoff [52]. This hydrologic export can reach $(180 \pm 12.6) \text{gm}^{-2} \text{d}^{-1}$, making it a major soil carbon loss pathway [14] that plays a significant role in salt marsh carbon cycling [15-16].

Tidal action and rainfall-driven runoff control water levels and flow velocities, directly affecting redox conditions [15,56] and carbon migration rates [57]. Tides create salinity gradients from sea to land, while drying-wetting cycles alter soil structure, controlling the balance between aerobic and anaerobic respiration and influencing organic carbon stability and microbial activity [15,60]. Although eddy covariance towers have quantified vertical carbon exchange [18-19,21-22], these measurements have not been coupled with lateral carbon flux assessments [16], limiting comprehensive carbon budget evaluation.

4. Effects of Tidal Action and Drying-Wetting Cycles on Carbon Sequestration Mechanisms

Lateral DOC, DIC, and POC fluxes are integral to carbon budget estimation, and the dynamic balance between carbon uptake and emission determines salt

marsh carbon sink function. Tidal action and drying-wetting cycles influence soil physicochemical properties [2,13,33], hydrology [13,42,61], redox status [15,56], and vegetation growth [12,18], thereby affecting carbon exchange magnitude, direction, and ultimately the transformation between carbon sink and source functions.

Intertidal wetlands may fix CO_2 under low salinity and high moisture but emit CH_4 under high salinity and low moisture. Net ecosystem productivity decreased by 40% when salinity increased alone, but showed no significant change when both salinity and hydrology were manipulated [40]. Drying-wetting cycles alter soil moisture conditions, determining oxygen availability and shifting wetlands between methanogenic and oxidative environments [34,45]. Water level positively correlates with CH_4 production but negatively with $\text{CO}_2:\text{CH}_4$ ratios [62], while tidal stage regulates these relationships [25]. Lateral carbon export represents a major soil carbon loss pathway, with tides playing a key role. High tide soil CH_4 emissions correlate positively with $\text{CO}_2:\text{CH}_4$ ratios [63-64], and drying-wetting cycles likely control carbon exchange magnitude, direction, and transformation, ultimately determining carbon sequestration mechanisms.

5. Research Gaps and Future Directions

Tidal salt marshes differ from other wetlands through periodic flooding and exposure with associated salt accumulation and leaching, creating unique biogeochemical cycles [29,33] that may control carbon exchange and budget balance. Sea level rise will alter tidal water levels, flooding frequency, and drying-wetting cycles (projected 0.26-0.55 m by 2100) [61], potentially affecting carbon sequestration mechanisms. While previous studies have examined CO_2 , CH_4 , and lateral carbon fluxes, the impacts of tidal hydrodynamics and periodic drying-wetting cycles on key carbon processes and sequestration mechanisms remain unclear. Isolated consideration of vertical or lateral fluxes limits accurate assessment of blue carbon capacity and constrains holistic understanding of coastal marsh carbon cycling.

Future research should strengthen investigations in four key areas:

1. **Systematic analysis of carbon exchange responses to different tidal stages:** Periodic tidal action subjects soils to dry-wet alternation cycles. According to tidal processes, soil moisture conditions can be divided into: drought stage (prolonged exposure), rewetting stage (tidal inundation), tidal flooding stage, and post-ebb wet stage [Figure 2: see original paper]. Carbon exchange processes respond differently to these stages, requiring mechanistic analysis.
2. **Microbial mechanisms of carbon exchange under tidal action:** Periodic drying-wetting cycles directly affect nutrient availability, soil temperature, salinity, oxygen environment [34,45], and redox status [15,56], altering microbial community structure, activity, and carbon utilization patterns [66], ultimately influencing carbon uptake and emission.

3. **Tidal hydrodynamic effects on DOC, DIC, and POC release:** Lateral carbon exchange between salt marshes and coastal waters significantly contributes to coastal carbon pool dynamics, yet research on tidal impacts on soil carbon stocks and export remains limited.
4. **Integration of tidal hydrodynamics into carbon cycle models:** Current coastal wetland carbon models treat ecosystems as homogeneous systems, ignoring tidal effects. Incorporating tidal hydrodynamic processes as variables will improve model accuracy and enable comprehensive assessment of salt marsh carbon sink functions through statistical and spectral analysis of tidal-carbon exchange relationships.

References

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