

Wetland Plant Community Succession and Carbon Sink Dynamics under Climate Change,

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Abstract:

Climate change is profoundly altering wetland plant community succession, with significant consequences for the stability and carbon sink capacity of these ecosystems. Rising temperatures, shifting hydrological regimes, sea-level rise, and extreme events reshape community composition through species turnover, trait adaptation, and altered assembly processes. Regional responses are diverse: tropical wetlands face mangrove retreat under sea-level rise and storm disturbance; temperate wetlands experience accelerated carbon mineralization under recurrent drought; and boreal peatlands diverge into drained sites that emit CO₂ and inundated zones that release methane. These dynamics are further shaped by feedback mechanisms. Positive loops, such as permafrost thaw and peat fires, intensify carbon losses, while negative buffers, including prolonged growing seasons and anoxic preservation of organic matter, partly mitigate emissions. Understanding these contrasting outcomes is crucial for predicting global carbon-climate interactions. Effective management demands region-specific approaches, including hydrological stabilization, restoration of degraded sites, and facilitation of species migration. Supported by remote sensing, long-term monitoring, and advanced modeling, such strategies are essential to safeguard wetland carbon services under future climate scenarios.

Keywords: Wetland Plant Succession, Carbon Sequestration, Climate Change Feedback, Blue Carbon

1. Introduction

Wetlands are globally significant carbon sinks, storing an estimated 20–30% of terrestrial soil carbon despite covering only 5–8% of the land surface.

Peatlands alone contain carbon equivalent to twice that stored in global forest biomass, underscoring their exceptional capacity for long-term sequestration [1,2]. However, climate change poses substantial threats to this function through multiple pathways.

While CO₂ fertilization and moderate warming may temporarily enhance productivity in some regions, key risks predominate: altered hydrology and permafrost thaw accelerate soil carbon decomposition. For example, Arctic peatland warming has been shown to increase soil respiration by approximately 28% per 1 °C [3], and model projections suggest that up to 40% of global peatlands could shift from carbon sinks to sources by 2100 [4].

Plant community succession plays a central role in mediating these carbon cycle responses. Shifts in species composition directly influence carbon input and stability; for instance, grass litter decomposes significantly faster than sedge litter [5]. Moreover, vegetation traits such as aerenchyma development and root exudation strongly regulate methane fluxes [6].

This review synthesizes current understanding of the interactions among climate change, wetland plant succession, and carbon cycling. Clarifying these mechanisms is essential to inform conservation strategies and to sustain vital “blue carbon” ecosystem services under future climate scenarios.

2. Key Climate Change Drivers and Their Overall Effects on Wetlands

2.1 Temperature and Precipitation Changes

Climate change reshapes wetlands through rising temperatures and altered precipitation. In coastal systems, the reduction of cold extremes facilitates mangrove expansion into areas historically dominated by salt marshes, resulting in complex and nonlinear latitudinal distribution shifts. Reduced rainfall drives vegetation loss in moderate-rainfall zones, expanding bare ground. Under warm and dry conditions, succulents and bare soils are favored, whereas warm and wet conditions promote the expansion of mangroves and grasses [7]. Inland peatlands respond to warming via plant trait shifts toward high-productivity species (increased leaf area, canopy height). Drying lowers water tables, accelerating peat decomposition, and weakening carbon storage [8]). These thermal and hydrological changes fundamentally alter wetland structure and function.

2.2 Cascading Effects of Sea-Level Rise

Sea-level rise (SLR) reshapes wetland landscapes through cascading effects of physical inundation and saltwater intrusion. When the rate of SLR persistently exceeds sediment accumulation capacity, salt marshes experience structural collapse. The breakdown of vegetation zonation leads to a collapse of structural integrity, thereby

undermining the wetland’s carbon storage capacity. Simultaneous seawater intrusion causes salinity gradients to shift landward in freshwater wetlands, driving mangrove expansion inland and altering carbon pool spatial distribution patterns [9,10]. This cascade threatens coastal wetland resilience.

2.3 Extremes and Biogeochemical Feedbacks

Hurricanes can cause large-scale mangrove mortality, resulting in immediate and substantial carbon release, while storm-driven sediment deposition provides only temporary compensation through short-term carbon burial [11]. Rising CO₂ has dual effects: enhanced C₃ plant photosynthesis boosts biomass but altered litter chemistry slows decomposition. Dissolved organic carbon surges stimulate methane production [6,12]. Elevated salinity levels impose stress on salt marsh grasses, thereby facilitating the expansion of salt-tolerant succulents and simultaneously suppressing microbial denitrification, which reduces both nitrogen removal and carbon fixation [13,14]. Permafrost degradation in cold wetlands accelerates ancient carbon mineralization and increases peat fire frequency, releasing stored carbon [3,15]. These feedbacks amplify climate-warming loops.

2.4 Synergistic Risk Amplification

Synergistic interactions among multiple factors significantly amplify ecosystem risks. The coupling of warm-drying and SLR accelerates salinization in Mediterranean freshwater wetlands, leading to persistent decline in carbon sequestration function. Permafrost thaw and wildfire interactions form a “carbon release-climate warming” positive feedback loop, pushing wetlands across ecological tipping points towards irreversible transition into net carbon sources [15-17]. Such synergistic interactions threaten to push wetlands beyond ecological thresholds, driving irreversible transitions from carbon sinks to persistent carbon sources.

3. Response Patterns of Wetland Plant Community Succession

3.1 Species Replacement

Climate-driven shifts in temperature, salinity, and water levels drive species turnover, with dominant factors varying by habitat. Mangroves (*Avicennia* spp.) expand into temperate salt marshes (*Spartina alterniflora*) as freezing events decline, aided by cold-tolerance genes (e.g., anti-freeze proteins). SLR-induced saltwater intrusion favors invaders like *Phragmites australis*, whose allelochemicals

(e.g., gramine) inhibit natives. Freshwater plants (e.g., *Zizaniopsis miliacea*) suffer reduced photosynthesis under osmotic stress. In lakes, salinity >20 causes ion toxicity, replacing submerged plants (e.g., *Chara aspera*) with mi-

crobial mats. Representative case studies of climate-driven species replacement in wetlands are summarized in Table 1.

Table 1. Key Case Studies of Species Replacement

Location	Climate Driver	Key Change	Source
Texas Coast	Reduced frost frequency	Mangrove area increased 74% (1990–2010)	Short et al.2016
Ameland Island, NL	SLR (soil subsidence)	Shift to wet-valley species, increasing salt-tolerant succulents	van Dobben & Slim 2012
Global lakes	Salinization	Submerged plants transform into Microbial mats	Short et al.2016

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3.3 Community Restructuring

Drought reduces biomass in xerophytes (e.g. *Elymus pycnanthus*), while salt-tolerant species (e.g. *Spartina patens*) gain competitive advantage through stomatal control—lowering diversity. SLR causes “coastal squeeze,” eliminating high-marsh specialists. On Ameland Island, SLR-driven changes caused loss of 6.5 species/plot over 15 years, though rare specialists persisted [18-19]. Warming + eutrophication shifts lakes from macrophyte-dominated to algae-dominated states by excluding submerged plants via shading/anoxia. Notably, Ameland’s biodiversity loss was primarily eutrophication-driven, weakening water purification via reduced nutrient uptake. These simplifications erode ecosystem multifunctionality.

3.4 Differential Responses

Lifeform dictates vulnerability: submerged plants (e.g. *Posidonia oceanica*) are heat-sensitive (>26°C causes mortality), while emergent (e.g. mangroves) suffer from SLR-induced root hypoxia. C₃ plants gain productivity under high CO₂; C₄ plants (e.g. *Spartina*) show minimal response. Salinity tolerance thresholds determine sur-

vival—freshwater plants (e.g. *Ruppia maritima*) decline at salinity >20, while euryhaline species (e.g., *Halodule wrightii*) tolerate 5–45 via salt glands (Short et al. 2016). By 2100, Ameland salt marshes may revert to pioneer stages, and dunes shift to wet-valley communities [19]. Functional traits thus govern asynchronous changes in carbon and biodiversity services.

4. Carbon Sink Response Pathways of Wetland Succession under Climate Change Disturbance

Under global climate change, wetland plant community succession trajectories are undergoing significant shifts. These shifts drive dynamic responses in carbon sink function by profoundly altering vegetation structure, biogeochemical cycles, and the physical environment. These response pathways exhibit significant regional variations but are also governed by key common ecological mechanisms.

4.1 Tropical Regions: Mangrove Succession and Carbon Pool construction

Mechanisms of carbon accumulation in tropical mangrove wetlands operate differently across successional stages. In the pioneer stage (e.g. *Avicennia marina* communities), species typically exhibit high growth rates and photosynthetic efficiency, producing large amounts of litter. This litter decomposes rapidly in warm, humid, decomposer-rich environments, effectively promoting surface soil organic carbon accumulation in the short term. High productivity is the main driver of carbon accumulation in this stage. As succession progresses to the mature stage (e.g. *Rhizophora* spp. and *Bruguiera* spp. communities), dominant species shift to trees with substantial above- and belowground biomass. Their litter, particularly coarse

woody debris rich in lignin and tannins (compounds resistant to decomposition), decomposes much slower. Simultaneously, dense root networks and structures like prop roots promote the physical protection of soil organic matter (e.g., through aggregation). These factors collectively lead to significantly prolonged carbon residence times, enabling long-term, stable carbon sequestration. Studies show that soil organic carbon burial rates in mature mangroves can be up to 1.8 times higher than in early successional stages, highlighting the core role of late succession in long-term carbon storage [20]. However, global climate change is profoundly disrupting this natural trajectory and carbon sink function. Accelerated SLR poses a severe threat to mature mangroves. When the SLR rate exceeds the vertical accretion rate of mangrove soils, mature mangroves (typically located at higher elevations further inland) experience intensified inundation stress and rising soil salinity, leading to tree mortality and ecosystem degradation. Succession reverses or stalls [21]. This degradation not only directly loses the vast mature carbon pool but also forces the ecosystem towards higher productivity but lower carbon storage pioneer stages or bare mudflats, significantly weakening long-term carbon sequestration capacity. Furthermore, increasingly frequent and intense tropical cyclones (hurricanes, typhoons) cause widespread physical damage and tree mortality, instantly converting large amounts of biomass carbon into debris. They may also disrupt soil structure, accelerating organic carbon decomposition and loss, effectively “re-setting” mature stands to early successional stages [22]. Additionally, while temperature increases may enhance mangrove productivity within certain ranges (especially at high-latitude margins), they also significantly increase soil heterotrophic respiration rates, accelerating soil organic carbon decomposition and potentially elevating methane (CH₄) emissions [23], partially offsetting the carbon sequestration benefits of increased primary production. It’s important to note that despite the strong sequestration capacity of the mature stage, its tidal environment may still generate some CH₄ emissions, although its net carbon sink effect typically remains significantly positive. Under climate pressure, maintaining the ecological integrity of mature mangroves and promoting their ability to migrate landward is crucial for safeguarding their function as a long-term, efficient “blue carbon” sink.

4.2 Temperate Regions: Carbon Dynamics in Herbaceous to Woody Succession

The impact of succession on carbon sink function in temperate wetlands (e.g. reed swamps, forested swamps) involves complex mechanisms. In the herbaceous suc-

cessional stage (e.g. *Schoenoplectus* spp. emergent communities), enhanced carbon sink capacity is primarily driven by rapidly increasing vegetation cover and significantly accumulating belowground biomass (roots, rhizomes), resulting in high photosynthetic productivity and substantial organic matter input. Crucially, persistent flooding maintains strong anaerobic conditions, strongly inhibiting microbial decomposition activity, thus facilitating effective organic carbon accumulation in the soil. For example, in the Mississippi River Delta, soil organic carbon accumulation rates increased by approximately 35% during succession from open water to emergent plant communities, highlighting the synergistic advantage of high productivity and low decomposition rates in this stage for carbon accumulation [24]. As succession progresses to the woody stage (e.g. *Taxodium distichum* forests), inputs of coarse woody debris (dead branches, fallen logs) become a significant carbon source. Their complex physical structure and chemical recalcitrance lead to substantially prolonged carbon residence times. However, dense canopy cover reduces light availability for ground-layer herbaceous plants, thereby suppressing photosynthesis and lowering their contribution to carbon sequestration. Consequently, while the woody stage stores large amounts of carbon (especially in biomass and large woody debris), its annual new carbon accumulation rate may be lower than that of highly productive herbaceous stages. Furthermore, the entire system becomes more sensitive to changes in hydrological conditions [25]. Climate change, particularly shifts in precipitation and temperature patterns, is drastically altering the hydrological regime of temperate wetlands, profoundly affecting their successional pathways and carbon balance. Increased frequency and intensity of drought events cause water level decline or even desiccation in many temperate wetlands[2]. Hydrological drying first threatens woody swamps dependent on stable deep water (e.g. cypress-tupelo forests), potentially causing their degradation or death and releasing stored carbon. Simultaneously, drying promotes oxygen diffusion into the soil, significantly accelerating the decomposition rate (mineralization) of soil organic matter, including historically accumulated carbon, potentially turning wetlands from sinks into carbon sources. Even without complete desiccation, increased hydrological variability (e.g., more frequent wet-dry cycles) can disrupt soil aggregate structure, exposing protected organic matter, and may stimulate microbial processes producing the potent greenhouse gas nitrous oxide (N₂O) [26], further weakening the net carbon sink effect. Rising temperatures also have dual effects: potentially extending growing seasons and boosting productivity in some wetland vegetation, while also accelerating soil organic carbon decomposition and methane

production. The high sensitivity of carbon sink function in woody-stage wetlands to hydrological disturbance means their ability to maintain high carbon stocks becomes extremely vulnerable under climate-induced “hydrological stress.” Assessing the net carbon sink effect at this stage requires integrating CO₂ uptake with potential CH₄ and N₂O emissions, especially in nutrient-enriched areas. Increased nutrient inputs from climate change (e.g., agricultural runoff from extreme rainfall) may further exacerbate N₂O emissions, making the net greenhouse gas balance of woody swamps more complex and potentially unfavorable under specific conditions [27]. Therefore, maintaining stable hydrological conditions is key to ensuring the sustained carbon sink function of temperate wetlands, particularly those in late-successional woody stages.

4.3 Boreal and High-Latitude Regions: Succession Imbalance under Permafrost Thaw

Surface warming rates in the Arctic over the past decade have exceeded the global average by more than threefold (+3.1°C), significantly accelerating permafrost thaw [28]. Climate warming-induced permafrost degradation has become a major disruptor of natural succession trajectories in boreal peatlands, profoundly altering their carbon sink/source function and leading to two distinct pathways. Thaw-driven disturbance operates through dual mechanisms: thickening of the active layer (average rate increase of 0.3 m/decade over ~40 years) disrupts original peat structure [29], and meltwater reconfigures microtopography and nutrient cycling, triggering vegetation community reorganization [30]. Along the drainage-degradation pathway, permafrost thaw enhances surface drainage, lowering peatland water tables and increasing oxidation. This drives ecosystem degradation towards herbaceous or shrub vegetation with lower productivity but accelerated decomposition rates. The core consequence is the accelerated decomposition of historically stored ancient peat carbon. Observations show soil organic carbon decomposition rates increase by 40–70% in drained areas [31], releasing large amounts of carbon dioxide (CO₂) and even nitrous oxide (N₂O), transforming wetlands from sinks into significant carbon sources and severely weakening or reversing their original carbon sink function [32,33]. Conversely, along the inundation-reestablishment pathway, permafrost thaw forms thermokarst depressions, leading to localized re-establishment of waterlogged conditions. These depressions promote the rapid replacement of original Sphagnum moss communities by wetter-adapted plants (e.g., sedges, *Carex* spp.) [34], restarting peat accumulation processes. However, persistent inundation creates potent methane (CH₄) production sources. Thermokarst ponds

exhibit CH₄ emission fluxes of 120–180 mg·m⁻²·d⁻¹, 5–8 times higher than in undegraded areas [35]. Although soil organic carbon accumulation increases, the surge in CH₄ emissions (with a global warming potential 28–34 times that of CO₂ over 100 years) can partially or fully offset the carbon sink gains from CO₂ uptake [33]. Therefore, accurately assessing the net climate effect of such successional pathways requires strict accounting of all greenhouse gas fluxes (CO₂, CH₄, N₂O) and their relative warming contributions, alongside quantifying the cascade effects of climate-hydrology-vegetation succession on carbon cycling [3].

5. Cascade Feedbacks in Climate-Vegetation-Carbon Cycle

5.1 Key Positive Feedback Loops

Climate change intensifies carbon loss from global wetlands through several positive feedback mechanisms. In Arctic wetlands, permafrost thaw induces ground subsidence and thermokarst development, enhancing organic matter decomposition and methane release. Shrub expansion further reduces albedo and amplifies regional warming. Studies show a 17±4% rise in carbon release per 1°C warming in Siberian peatlands. During droughts, tropical peat swamps undergo rapid carbon oxidation and wildfire-driven emissions, with carbon losses reaching up to five times the mean annual rate. In temperate coastal wetlands, warming accelerates soil carbon mineralization; for instance, rates in Chesapeake Bay increased by 130% above 28°C compared to 20°C, weakening their carbon sink function.

5.2 Negative Feedback Buffering Mechanisms

Certain ecosystems exhibit compensatory mechanisms that partially buffer carbon losses. In boreal peatlands, extended growing seasons under warming stimulate plant growth and carbon uptake. Elevated CO₂ concentrations (560 ppm) have been demonstrated to enhance carbon sink capacity by 12–18%. Amazonian floodplain wetlands maintain relatively stable carbon storage through seasonal flooding that limits decomposition; even with 2°C warming, carbon stocks may vary within ±5%. Alpine wetlands on the Tibetan Plateau see reduced soil carbon mineralization (by 19%) due to root-derived compounds that suppress microbial activity. These negative feedbacks play a critical role in moderating climate-induced carbon emissions. Overall, wetland carbon dynamics reflect a balance between positive feedbacks that accelerate carbon loss and negative feedbacks that promote carbon retention

or uptake.

5.3 Pulse Disturbance Effects

Pulse disturbances cause complex, multi-phase impacts on wetland carbon cycles. Short-term effects frequently involve rapid carbon loss, as observed during extreme droughts (e.g., a 32% decline in Australian marsh carbon stocks) or storm surges (e.g., a 2.8-fold increase in organic carbon export in East Asian estuaries). In contrast, sudden flooding events can introduce large quantities of terrestrial carbon, temporarily elevating burial rates—such as the 150% increase following the 2011 Mississippi flood. However, these immediate carbon gains may be offset by long-term ecosystem shifts, such as vegetation transition toward lower-biomass species, ultimately reducing sequestration capacity. Recovery timelines also vary: erosion-induced carbon loss may require 5–8 years for rebound, whereas vegetation and functional recovery after drought can be even slower. Thus, pulse disturbances trigger not only abrupt carbon releases but also prolonged functional alterations, shaping the trajectory of wetland carbon storage over time.

6. Management Implications and Future Directions

6.1 Management Implications

Documented evidence shows that global climate change is altering wetland plant community dynamics and reducing their carbon sequestration capacity. Therefore, it is essential to formulate region-specific adaptive management strategies. In Arctic and boreal wetlands, where permafrost thaw and peatland desiccation represent major threats to carbon storage, management efforts should focus on sustaining elevated water tables to reduce organic matter decomposition and limit wildfire susceptibility. Practical measures may include the blocking of drainage ditches to reestablish hydrological connectivity [34]. Concurrently, it is critical to monitor the rate of expansion and the spatial extent of woody plant invasion into tundra wetlands given its influence on surface albedo and permafrost stability [35–37].

In temperate wetlands, altered precipitation regimes and increased frequency of extreme climatic events necessitate management approaches aimed at improving ecosystem resilience. Such strategies encompass integrated watershed-level water resource management to ensure ecological water allocation, rehabilitation of riparian vegetation buffers to reduce flood-induced erosion and enhance pollutant filtration, and the assisted migration or introduction

of plant species capable of tolerating new climatic conditions to preserve community integrity and functionality [2,38].

In tropical and subtropical wetlands—such as mangroves and peat swamps—where sea-level rise and saltwater intrusion constitute urgent challenges, adaptation strategies should incorporate nature-based solutions. These include enabling the inland migration of mangroves in conducive coastal settings, restoring natural tidal flows to counteract saltwater intrusion, and enforcing stringent conservation policies to protect intact peat swamp forests and prevent their conversion into carbon sources through drainage or degradation [39,40]. Collectively, these regionally differentiated management frameworks highlight the importance of context-specific approaches to maintain wetland carbon sinks under climate change.

6.2 Future Research Directions

Advancing the understanding of wetland carbon sinks requires an integrated research agenda built upon three interconnected pillars. First, there is a need to establish globally coordinated long-term observational networks capable of synthesizing multi-scale data—from genomic to ecosystem levels—to elucidate how interactions between biological and environmental factors shape carbon flux dynamics. Building on such empirical foundations, efforts should focus on refining coupled hydro-biogeochemical-vegetation models to improve predictions regarding the spatiotemporal evolution of wetland carbon sequestration under future climate scenarios. Finally, comprehensive regional assessments of emerging management strategies—such as controlled rewetting, assisted species establishment, and soil carbon amendment techniques—are essential to evaluate their ecological efficacy, carbon sequestration potential, and long-term viability. Such evaluations will provide a scientific basis for developing cost-effective and ecologically sound wetland management protocols.

7. Conclusion

Climate change is profoundly altering the successional pathways of wetland plant communities worldwide, thereby reshaping the stability and functionality of their carbon sink capacity. Multiple drivers—including rising temperatures, altered hydrological regimes, sea-level rise, and increased frequency of extreme climatic events—affect carbon cycling through processes such as species filtering, trait adaptation, and community reassembly.

Regional responses exhibit distinct patterns. Tropical wetlands may experience short-term carbon gains through mangrove expansion, but these are often offset by long-

term losses associated with submergence and ecosystem degradation. Temperate wetlands benefit from extended carbon residence times under woody encroachment, yet remain highly vulnerable to accelerated carbon mineralization during droughts. Boreal peatlands follow divergent trajectories: drainage promotes decomposition of ancient peat carbon, whereas inundation facilitates renewed sequestration but simultaneously enhances methane emissions.

Feedback mechanisms further modulate these dynamics. Positive feedbacks, such as permafrost thaw–albedo interactions and peat fires, amplify carbon losses, while negative feedbacks, including plant physiological regulation and anoxia-induced preservation, provide partial buffering effects.

Looking ahead, the sustainability of wetland carbon sinks will depend on the implementation of ecosystem-specific management strategies. Key priorities include maintaining high water tables in Arctic peatlands, stabilizing hydrological regimes in temperate systems, and enabling landward migration of mangroves in coastal zones. To achieve these goals, it is essential to strengthen integrated long-term monitoring, refine process-based modeling, and evaluate the effectiveness of intervention measures. Such actions are critical for advancing climate-resilient wetland management and securing the role of global blue carbon reservoirs in climate change mitigation.

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