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Review Article

Floodplains and coastal wetlands as nutrient sinks: a restoration perspective

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Abstract

Floodplains and coastal wetlands provide essential ecosystem services such as flood protection, water quality enhancement, carbon sequestration, and the production of raw materials and food. Despite numerous studies on wetland restoration, the complexities of restoring ecosystem functions remain challenging. Complete restoration of natural functions is rare, and therefore seldom the primary target; instead, restoration efforts typically focus on reactivating key ecological processes. This study examines the restoration of ecosystem functions in floodplains and coastal wetlands, focusing on water quality improvement. It summarizes both nitrogen and phosphorus dynamics, highlighting the potential to restore processes like denitrification and sedimentation within relatively short time frames using selected case studies from Central Europe. However, restoration success is hindered by altered soil properties, nutrient legacy, and other degradation-related constraints. Ultimately, the effectiveness of restoration endeavors depends on site-specific factors such as wetland degradation, size, hydrological connectivity, plant recovery, and ongoing global changes. This underscores the importance of considering both spatial and temporal dimensions and adopting a custom-tailored restoration strategy.

Highlights

- Recovery of nutrient retention processes can be either rapid or delayed
- Nutrient legacies and soil degradation hinder ecosystem restoration.
- Process insights and site traits guide effective restoration efforts.

Key words: Anthropogenic pressures, denitrification, ecosystem services, hydrological connectivity, nitrate, nutrient retention, phosphorus, water quality

Nutrient retention processes in wetlands

Wetlands in their natural state provide vital ecosystem services, including water purification, biodiversity support, flood regulation, and carbon sequestration (Bonn et al. 2016; Kaden et al. 2023a). Among these, nutrient retention is particularly critical in floodplains and coastal wetlands (Fisher and Acreman 2004). Historically, wetlands have been integral to human civilization due to their fertility from regular flooding and the deposition of nutrient-rich sediments. The ancient Mesopotamian region, known as the "cradle of civilization", flourished in such environments, using the fertile soils for agriculture (De Klerk and Joosten 2021). Today the "Marsh People" still utilize these areas, though only in the greatly diminished remnants of their original territory (Fawzi et al. 2016). Understanding nutrient retention mechanisms in wetlands is crucial for maintaining or improving this function as part of their broader multifunctionality and for developing effective restoration and conservation strategies (Jurasinski et al. 2020; Zak et al. 2022).

Wetlands, including estuaries, salt marshes, mangroves, and riverine floodplains, are highly effective at nutrient mitigation due to their natural hydrology (Kaden et al. 2023a). These dynamic ecosystems undergo periodic or seasonal water level fluctuations, which affect their nutrient processing efficiency. During high flows, large quantities of nutrients from upstream sources (Kronvang et al. 2012; Poulsen et al. 2014) are transported into inundated wetlands, where they are retained by various processes (Fig. 1). However, depending on the flood duration, some phosphorus (P) and nitrogen (N) may be re-mobilized from the sediments, particularly under anaerobic conditions (Audet et al. 2011; Wang et al. 2023).

Nutrient removal in wetlands is driven by a complex interplay of hydrological, physical, chemical, and biological processes (Noe 2013). These processes include sedimentation, denitrification, anammox, P sorption, plant uptake, and microbial transformations, which are also mimicked and exploited for water purification in treatment wetlands. The pathways of water flow – such as surface runoff, groundwater, flooding, or tidal exchanges – ultimately determine the nutrient cycling processes and quantities (Fig. 1).

Coastal wetlands, influenced by tidal action, play a crucial role in nutrient cycling by facilitating the exchange of water and nutrients between wetlands and adjacent marine environments (Wang et al. 2023). The efficiency of nutrient retention in coastal wetlands depends on factors such as tidal frequency, water residence time, and the coupling between terrestrial and marine nutrient cycles. Additionally, the distinct microtopography of coastal wetlands, along with patches of varying plant communities, determines the trapping of sediment-bound nutrients in wetland soils or their uptake by plant roots and microorganisms (Weil et al. 2020; Gios et al. 2024). Both in coastal wetlands and floodplains, the following processes are intimately connected to maintaining nutrient cycling and removal:

1. **Sedimentation:** Wetlands with slow-moving or stagnant water act as natural filters trapping inorganic and organic matter containing nutrients attached to particles. Studies have shown that floodplains and coastal wetlands can retain more than 10 kg of phosphorus per hectare per year, respectively – one to two orders of magnitude higher than in other wetland types like minerotrophic peatlands (Mitsch and Reeder 1991; Hoffmann et al. 2009; Walton et al. 2020). The dynamic process of sedimentation and eventual resuspension is regulated by a variety of physical, chemical, and biological factors:
   - Hydrological conditions: Water flow velocity significantly influences sedimentation (Mitsch and Reeder 1991). When a stream overflows its

banks, the flow velocity decreases abruptly, allowing suspended material to deposit in floodplains. Similarly, suspended sediment deposits in coastal wetlands when tidal cycles stagnate and flow velocities approach zero. The intensity and frequency of flooding affect both the amount, type, and location of sediment in the flooding areas (Kronvang et al. 2009; Cabezas et al. 2010; Poulsen et al. 2014).

- Water chemistry: The chemical composition of water, including dissolved organic matter and certain ions, promotes flocculation, causing particles to aggregate and settle. Higher concentrations of suspended solids, that can hold nutrients, also enhance sedimentation by increasing particle density (Gregory and O'Melia 1989; Thomas et al. 1999).
- Vegetation and root structure: Wetland plants help retain sediments by reducing the water flow, promoting particle deposition and preventing resuspension and bank erosion, in particular when trees grow along the stream channels (Holguin et al. 2001; Kronvang et al. 2012; Curran and Hession 2013).
- Sediment type and source: Coarse particles like sand settle more quickly in low-flow areas, while finer particles like clay, silt, and organic matter remain suspended longer (Cabezas et al. 2010; Poulsen et al. 2014).
- Biological activity: Microbes may enhance sediment retention (Hopkinson et al. 2019) by binding particles, while bioturbation by organisms like worms and crustaceans can reduce it by mixing soil layers, thereby influencing sediment distribution and retention (Widdows and Brinsley 2002; Gerbersdorf and Wieprecht 2014).

2. **Microbial transformations:** Wetlands support a diverse community of microorganisms, including bacteria, fungi, and algae, which play key roles in nutrient cycling and removal (Wang et al. 2021). Denitrification, ammonium assimilation, nitrification, dissimilatory nitrate reduction to ammonium (DNRA), anaerobic ammonium oxidation (anammox) (Burgin and Hamilton 2007; Sgouridis et al. 2011; Welti et al. 2012; Zhu et al. 2013; Hoagland et al. 2019; Wang et al. 2020), and mineralization of organic matter contribute to the nutrient dynamics of wetlands. The efficiency of these processes is shaped by environmental factors such as water chemistry, temperature, and organic matter availability (Gios et al. 2024), which influence microbial community structure and function (Weil et al. 2020). Additionally, plant-microbe interactions enhance nutrient cycling, with plants providing a substrate for microbial growth while benefiting from microbial nutrient transformations (Gutknecht et al. 2006; Morris et al. 2013).

   Denitrification, where nitrate is reduced to nitrogen gases (N_2 and N_2O) and permanently removed from the aquatic system, is a key process of water purification in wetlands, mainly occurring under anaerobic conditions in waterlogged soils or sediments. In floodplains and coastal wetlands, denitrification can be highly efficient, particularly during flooding events when nitrate-enriched water influxes lead to a N removal efficiency often exceeding 90% in waterlogged riparian zones (Lind et al. 2013). However, at elevated nutrient loads, bacterial denitrification may be limited by the availability of carbon, which is necessary as an energy source and electron donor to reduce nitrate (Walton et al. 2020). Surprisingly, nitrate retention efficiency in organic soils (53 ± 28%) was only slightly higher than in mineral soils (50 ± 32%) (Walton et al. 2020). This process is temperature-dependent, but significant nitrate removal can occur even at low temperatures (< 5 °C) during winter (Hoffmann et al. 2019). Its effectiveness can decline under fluctuating water tables, low pH (< 5–6), or high nitrate concentrations, leading to incomplete denitrification and the release of N_2O, a potent greenhouse gas (Lind et al. 2013; Gios et al. 2024). In addition to microbial denitrification, an abiotic process involving nitrate reduction through pyrite oxidation has been observed in carbon-poor groundwater systems (Jessen et al. 2017).

3. **Sorption and precipitation:** Phosphorus (and ammonium) is often retained in wetland soils through sorption to iron, aluminum, and calcium minerals, as well as by precipitation as insoluble compounds (Florea et al. 2024). In calcium-rich wetlands, P can precipitate with calcium to form calcium phosphate minerals, typically under alkaline conditions (Reddy et al. 1999). Furthermore, P may be sorbed onto organic matter and clay minerals (Couic et al. 2022). Due to the negative charge of the phosphate species at pH > 2 and the isoelectric point of charge of metal oxides in the circum-neutral range, P binding is favored at pH ranges of 4–6. Phosphorus sorption in coastal wetlands might be outcompeted by high concentrations of sulfate, which replaces P from positively charged binding sites (Beltman et al. 2000). High sulfate loading can significantly alter the P cycle in wetland systems when sulfate is reduced to sulfide in anaerobic sediments, promoting sulfate-mediated P mobilization or internal eutrophication (Zak et al. 2021).
4. **Plant uptake:** Wetland plants, including submerged and emergent vegetation, play an essential role in nutrient uptake (Walton et al. 2020). These plants assimilate nutrients like N and P into their biomass, reducing nutrient concentrations in the water and soils. As plants grow and decompose, nutrients remain trapped within the wetland ecosystem, further supporting nutrient cycling and temporarily retaining nutrients until senescence. Mangroves and salt marshes are particularly effective in this regard (Vernberg 1993; Reef et al. 2010).

The effects of altered site characteristics, catchment, and climate

The effectiveness of nutrient removal in floodplain and coastal wetlands is strongly influenced by changes in hydrology, land use, and climate. Human activities, such as land reclamation, urbanization, and agricultural intensification, have globally altered these systems (Tockner et al. 2009; Li et al. 2018; Hopkinson et al. 2019), often impairing their function as nutrient and carbon sinks (Jurasinski et al. 2020; Zhang et al. 2023). Climate change introduces additional complexity with changes in precipitation, sea-level rise, and more frequent extreme hydro-climatic events. Among these factors the following three significantly limit the nutrient sink capacity of wetlands under changing environmental conditions.

1. **Wetland loss and fragmentation:** Hydrological connectivity is a key factor controlling the sink function of wetlands, as it facilitates nutrient exchange between aquatic and terrestrial environments (Natho et al. 2020). Fragmentation leads to smaller, isolated, and hydrologically disconnected wetlands, which impairs this exchange, thereby reducing nutrient removal efficiency

and weakening the resilience of wetlands to environmental stressors such as climate change and pollution (Tockner et al. 2010; Wu et al. 2022).

2. **Pollution and eutrophication:** Excessive nutrient loading from agricultural runoff, wastewater discharge, and urban development leads to nutrient pollution, primarily N and P. This may have severe environmental consequences, such as eutrophication, hypoxia, and harmful algal blooms, degrading water quality and disrupting aquatic life (Häder et al. 2020; Petersen et al. 2021). Wetlands play a crucial role in absorbing and processing excess nutrients, making them essential in water management strategies (Pedersen et al. 2007; Hoffmann et al. 2020; Zak et al. 2022, Hermansen et al. 2026). In coastal areas, agricultural runoff and wastewater discharge often contribute to excessive nutrient loads, exacerbating eutrophication and leading to harmful algal blooms, oxygen depletion, and fish kills, as frequently documented for the Baltic Sea over the last century (Carstensen et al. 2014).
3. **Climate change:** Climate change presents several challenges for wetland nutrient removal. Rising temperatures, altered precipitation patterns, and more frequent droughts can affect soil chemistry and microbial processes like denitrification, potentially impacting nutrient cycling efficiency and increasing greenhouse gas emissions (Stirling et al. 2020). Furthermore, sea-level rise particularly threatens coastal wetlands by increasing erosion, altering salinity, disrupting nutrient cycling, and causing habitat loss, especially for less salt-tolerant species (Anderson et al. 2022). Even low levels of increased salinity may have a profound effect on P cycling, reshaping microbial community composition and promoting internal P mobilization in surface sediment (Hu et al. 2021).

Restoring the nutrient sink function

Restoring the nutrient sink function of coastal wetlands and floodplains is vital for addressing nutrient pollution and mitigating its harmful effects on aquatic ecosystems (Tschikof et al. 2022; Kaden et al. 2023b). Restoration efforts should focus on rehabilitating the hydrological, physical, chemical, and biological processes that support nutrient sink functions, while also carefully considering socio-economic aspects (Gumiero et al. 2013). Restoration does not necessarily lead to all-natural processes, even if natural conditions are created and the “physical structure for a particular ecosystem and the biotic composition and function will self-assemble”, as stated in the study by Hilderbrand et al. (2005). This also applies to re-establishment of the microbiome, which can take several years (Wen et al. 2018). Successful restoration projects must restore hydrological connectivity, enhance sediment and nutrient dynamics, and re-establish critical ecosystem processes, such as denitrification and P sorption (Li et al. 2018). It is important to note that side effects and potential conflicts of interest may arise during the early stages of restoration activities (Zak and McInnes 2022), making each restoration effort site-specific. To effectively restore the ecosystem functions of floodplains and coastal wetlands, a range of strategies must be considered.

1. **Restoring hydrological connectivity:** Restoring their natural hydro-morphology is crucial for the nutrient removal function of wetlands and floodplains

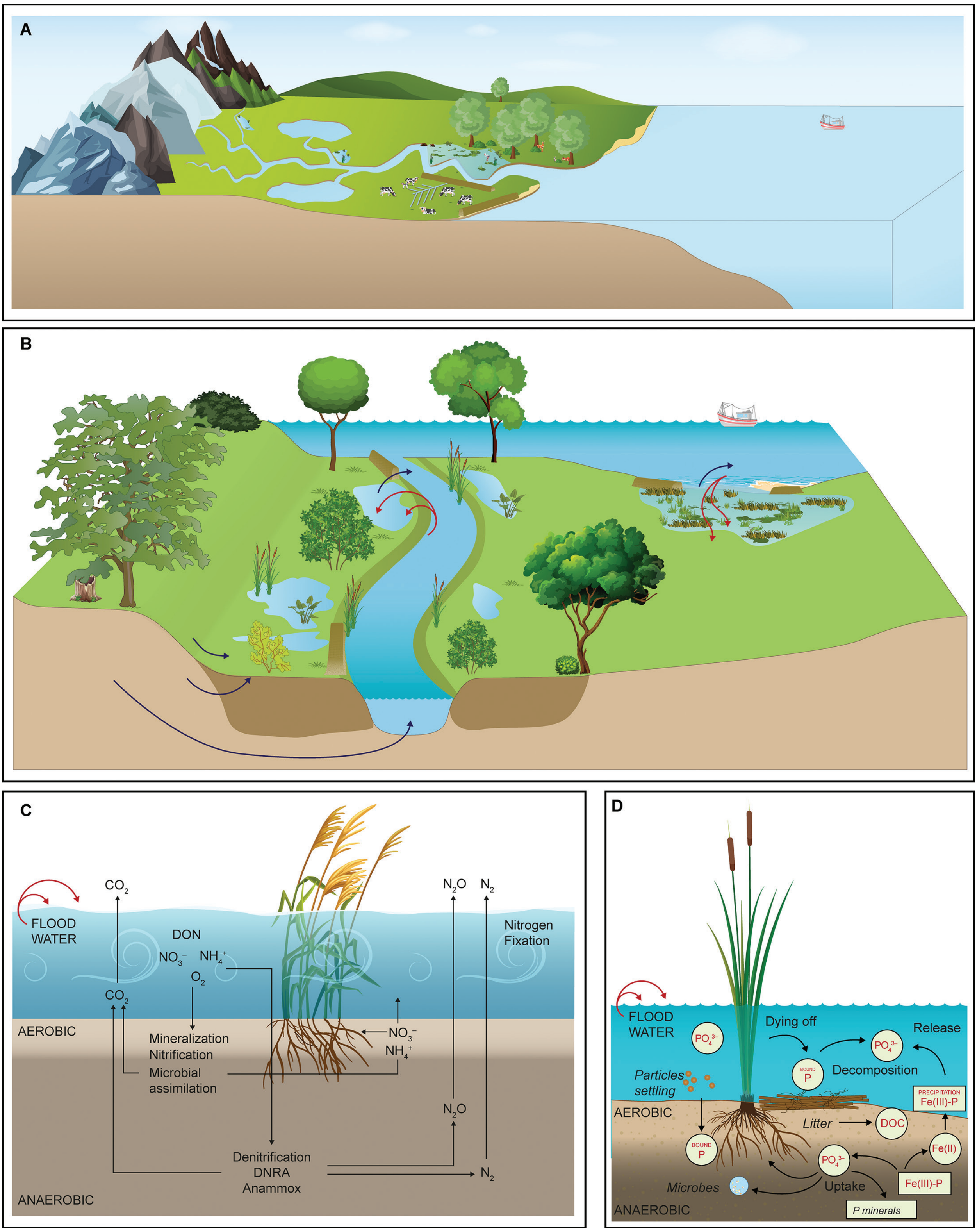
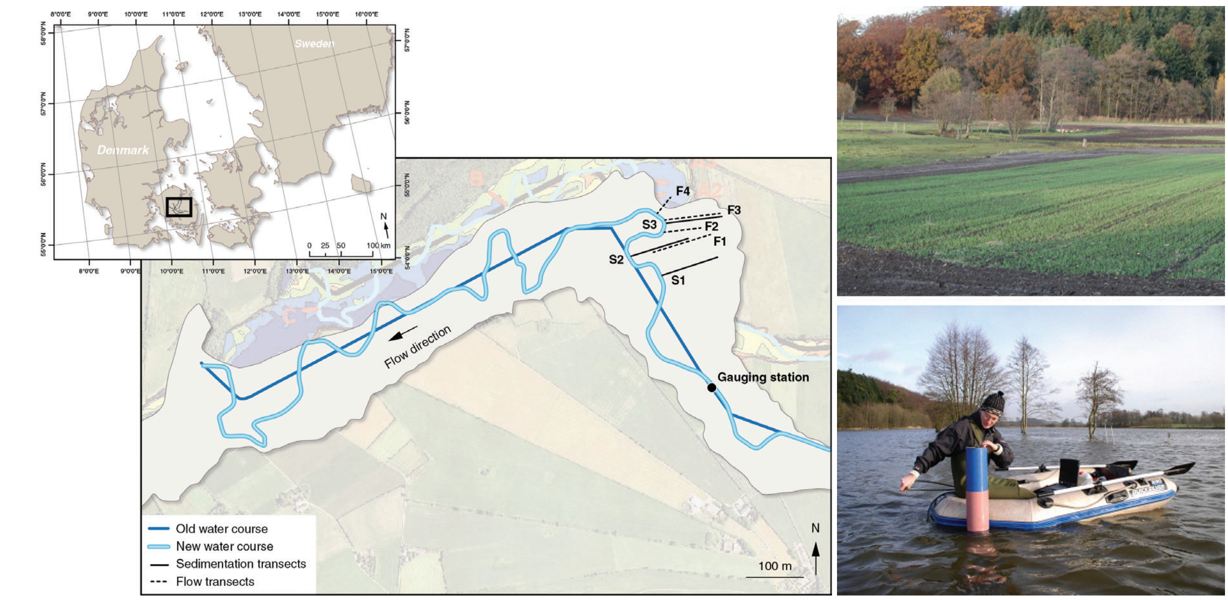


Figure 1. A, B. Schematic representation of a riparian landscape featuring smaller and larger floodplains, as well as coastal areas, either in a natural state or modified by drainage systems and embankments for agricultural use. **C, D.** Key biogeochemical processes driving nitrogen (N) and phosphorus (P) cycles under flooded conditions. Nitrogen-related processes involve CO_2 (carbon dioxide), N_2 (atmospheric N), N_2O (nitrous oxide), DON (dissolved organic nitrogen), NO_3^- (nitrate), NH_4^+ (ammonium), O_2 (oxygen), and processes such as DNRA (dissimilatory nitrate reduction to ammonium), and anammox (anaerobic ammonium oxidation). Phosphorus-related processes involve PO_4^{3-} (phosphate), Fe(III) (ferric iron), and Fe(II) (ferrous iron). (**D**) Arrows indicate predominant water flow paths, with substantial groundwater inflow in coastal wetlands.

(Hein et al. 2004; Acreman et al. 2007). The natural movement of water through wetlands – seasonal flooding and tidal exchange – is essential for effective nutrient processing. Wetland degradation often results from disruption of these hydrological regimes due to damming, diking, drainage, and land reclamation for agriculture (Gumiero et al. 2013; Zhang et al. 2023). Restoring hydrological connectivity aims to re-establish natural water flow patterns, allowing wetlands to receive and process nutrients from surrounding areas. For floodplains, this typically involves filling ditches and drains, reconnecting the groundwater flow to the riparian aquifer, re-meandering channels, removing or breaching embankments, reconnecting the floodplain and side-channels to the river, and reinstating natural surface flow dynamics (Buijse et al. 2002). This promotes sediment deposition, trapping nutrients in the wetland soil and preventing their downstream transport. However, incubation experiments from a Danish study site (see Box 1) revealed that between 11% and 25% of the P deposited on the floodplain could be released as dissolved inorganic P following deposition. Similarly, in coastal wetlands, restoring tidal flows enhances the water exchange be-

Box 1. Hydrological and ecological impacts of river re-meandering: A 20-year case study.



Figures: Left: Restoration of River Odense in southern Denmark. Right: Before and after flooding the riparian area.

In 2003, a 6.5 km stretch of River Odense was re-meandered, allowing natural inundation of the floodplain every winter (9–73 days from 2006–2012). This led to a successful restoration of natural processes, enhancing the nutrient sink function.

Over the last 20 years, various studies have been carried out to measure and model surface flow conditions, sedimentation processes, groundwater processes, biodiversity and in situ denitrification. MIKE21, a 2D dynamic river and floodplain model was established and validated against in situ measurements of flow velocities and depths on the floodplain (Poulsen et al. 2014).

Sedimentation rates on the floodplain varied considerably between years from 0 to 11 kg DW m^{-2} yr^{-1} (dry weight) during 2003/04 to 2011/12 (Blake et al. 2022).

Tracer measurement (137Cs) indicated a longer-term average sedimentation rate of 6 kg DW m^{-2} yr^{-1} (Blake et al. 2022).

Deposition of organic matter and total phosphorus averaged 0.65 kg m^{-2} yr^{-1} and 11.4 g P m^{-2} yr^{-1} in winter 2011/12 (Poulsen et al. 2014).

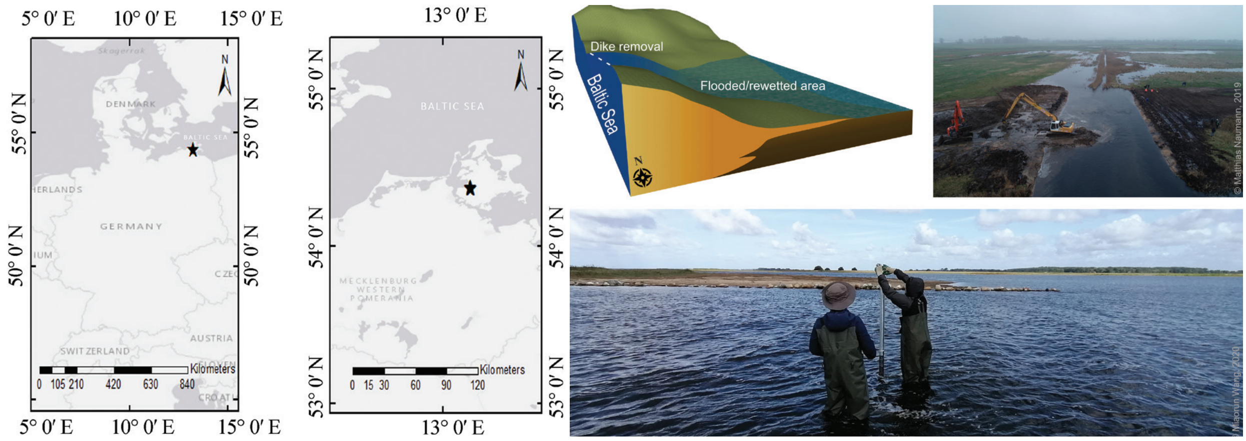
Seed richness, diversity, and composition from winter-deposited sediment varied with increasing distance from the river channel, peaking at 16 m with 10.7 ± 1.5 species, coinciding with a confluence zone emerging within the floodplain (Riis et al. 2014).

Flooding enhanced nitrate removal in groundwater (20 to 42 kg N ha^{-1} yr^{-1}) by creating a stagnant zone beneath the floodplain, increasing the residence time and upward flow into the highly reactive organic-rich topsoil (Kolbjørn Jensen et al. 2017).

tween the wetland and the adjacent marine environment, supporting nutrient cycling and improving the removal or storage of excess N and P.

2. **Enhancing sediment trapping, plants, and microbial communities:** Wetlands act as natural sediment traps. Restoration projects can include re-meandering rivers, restoring sediment delivery systems, and reintroducing sediment flows to floodplains. In coastal wetlands, sediment management strategies, such as mangrove restoration or sediment augmentation, can help restore sediment deposition processes and improve nutrient retention (Reef et al. 2010). Native plants contribute to nutrient uptake, and their biomass enhances microbial activity. In floodplains, riparian vegetation helps reduce nutrient runoff, while in coastal wetlands, mangroves, seagrasses, and salt marshes play a crucial role in nutrient transformation (Vernberg 1993; Holguin et al. 2001).
3. **Managing nutrient inputs:** Restoration efforts must also focus on reducing external nutrient loading from agricultural runoff. This may involve adopting best management practices in agriculture, reducing fertilizer use (Hoffmann et al. 2020), or creating buffer zones (Kronvang et al. 2024). Effective nutrient management can help alleviate the nutrient burden on wetlands, allowing them to develop as natural biodiversity hotspots in the landscape and provide important ecosystem services, such as flood water storage and nutrient retention and transformation. Without such an input reduction, the restoration of targeted plant communities might be delayed by decades (Baumane et al. 2021). While reducing external nutrient inputs is essential, restoration efforts must also address the internal nutrient dynamics within wetlands. Local variation in soil properties and microtopography, particularly in low-lying areas, can create hotspots for nutrient release during rewetting, which may exacerbate eutrophication pressures and hinder the recovery of ecological balance, as demonstrated for a coastal wetland (see Box 2).
4. **Addressing climate change impacts:** Climate change mitigation and adaptation strategies are essential components of wetland restoration. For example, enhancing wetland areas by sediment accretion can help coastal wetlands keep pace with sea-level rise. Additionally, floodplain restoration projects may need to account for changing precipitation patterns to restore hydrological dynamics (Carstensen et al. 2023) and counteract more frequent droughts by measures such as closing ditches and drainages (Wilson et al. 2011) or reconnecting water bodies. For example, a modeling study of a Danube floodplain found that side-channel reconnections could compensate for the reduced nutrient retention capacity in dry hydrologic years (Natho et al. 2020) (see Box 3).
5. **Monitoring and adaptive management:** Ongoing monitoring and adaptive management, as suggested by the IUCN standard (IUCN 2020), are essential for ensuring the success of restoration projects (Zedler 2017). This approach combines scientific monitoring, stakeholder engagement, and adaptive decision-making to ensure the success and sustainability of conservation efforts. Continuous assessment of ecological functions and services, such as biodiversity and water quality (e.g. nutrient concentrations) (see Box 4), help guiding restoration efforts and allows for adjustments based on environmental changes (Sandin et al. 2022).

Box 2. Spatial heterogeneity in a coastal peatland rewetting project: Elevation-driven nutrient release hotspots and SOM distribution.



Figures: Left: Location of the coastal peatland study site on Rügen Island in Germany. Right: Schematic illustration of topographic changes and field photos showing dike removal (©Matthias Naumann) and the floodplain post-restoration (©Miaorun Wang/Erwin Don Racasa/Simeon Choo).

The "Polder Drammendorf" coastal fen peatland (54°22'23.4"N, 13°14'27.2"E) is located on Rügen Island, Germany, approximately 12 km from the center of Stralsund City in the federal state Mecklenburg-Western Pomerania. As part of the coastal landscape transformation project "Renaturation Polder Drammendorf", the site was rewetted during winter 2019 through dike removal and is now permanently flooded by Baltic Sea water.

This case study analyzed elevation-dependent soil characteristics through: (1) RTK-GPS microtopographic surveys at 40 sampling points, (2) soil organic matter (SOM) content analysis of 80 soil samples (two depths), and (3) ammonium (NH_4^+) release quantification using nine intact soil cores grouped by elevation under simulated groundwater-brackish rewetting conditions (Wang et al. 2023).

Results showed significant spatial variability in elevation, SOM content, and NH_4^+ release behavior. A strong negative correlation was observed between SOM content and elevation (Pearson correlation coefficient $r = -0.64$, $p < 0.0001$), indicating restricted organic matter mineralization in low-lying areas.

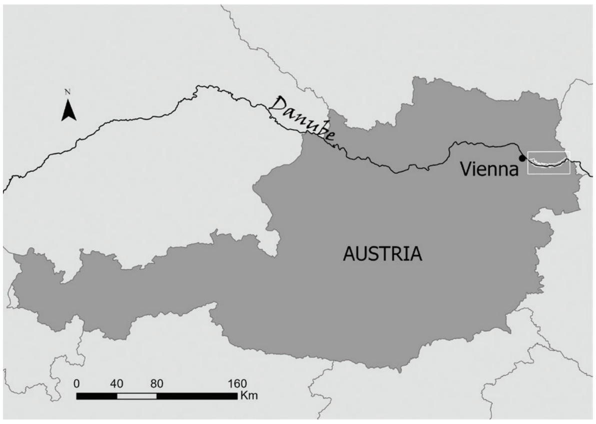
Soils at low elevations (< −0.6 m) released significantly higher NH_4^+ concentrations (initial leaching: 10.08–47.64 mg L^{-1}) compared to high-elevation soils (0–3.58 mg L^{-1}), with peak levels exceeding both the brackish rewetting solution (0.037 mg L^{-1}) and typical Baltic Sea waters (0–0.36 mg L^{-1}, equivalent to 1.5–20 µmol L^{-1} recorded by Naumann et al. (2020) and Berg et al. (2014) by approximately two orders of magnitude.

These findings identify low-lying areas in Drammendorf as critical nutrient hotspots during initial rewetting stages, potentially creating a significant eutrophication pressure on connected marine ecosystems (Wang et al. 2023).

To sum up and where do we go from here?

Floodplain and coastal wetlands are irreplaceable ecosystems that provide vital services, particularly flood regulation, nutrient removal, and biodiversity hotspots. Through processes like sedimentation, denitrification, P sorption, plant uptake, and microbial transformations, these ecosystems mitigate nutrient pollution and contribute to aquatic ecosystem health. However, human activities and climate change threaten the ability of these wetlands to perform their essential services and functions. To protect and restore these ecosystems, the restoration of the hydrological connectivity is essential and a multifaceted approach is required. This includes habitat conservation, pollution reduction, climate change adaptation, and active restoration efforts, while addressing societal needs. Potential conflicts can be mitigated by an inclusive approach and setting realistic, achievable restoration goals from the outset. Research should integrate various disciplines and methodological approaches, including hydrology, ecology, remote sensing, and socio-economics, to develop scalable solutions that can be communicated and implemented at larger

Box 3. Modeling nutrient retention in floodplain reconnection scenarios.



Figures: Left: Location of the national park "Donau-Auen" along the Danube east of Vienna. Right: One of seven side-channels to be reconnected, with the Danube's main channel in the background. © Natho 2019

Along its largest free-flowing section (36 km), the Austrian Danube River is fast-flowing and retains the dynamic character of a mountain river. The nutrient retention capacity of the side-channel system in the floodplain national park "Donau-Auen" was modeled and the impacts of an ambitious restoration plan were assessed. One measure was the reconnection of seven side-channels to the main river at low water levels. Nitrogen (N) and phosphorus (P) concentration data were collected at the in- and outlets of differently connected side-channels from two decades of monitoring. The concentration differences over space and time were then correlated with hydro-morphological factors to estimate nutrient retention in different hydrological years and to develop a scenario of full reconnection. Both, a statistical approach and a larger-scaled semi-empirical approach, based on transferable denitrification and sedimentation causalities (Venohr et al. 2011) were compared, to investigate the behavior and plausibility of both models (Natho et al. 2020).

Depending on the approach, discharge or hydraulic load drove the nutrient retention rates. The statistical model captured short-term responses in more detail than the semi-empirical model, which – in contrast – appeared more robust in assessing higher discharge and restoration effects. Overall, both results were similar, and the system holds more nutrients in better-connected side-channels during wet years. During hydrological disconnection with the main river, N – but not P – concentrations decreased in the side-channels. During surface-water connection, N retention rates quickly exceeded those during disconnection, and a slight P release was observed at low discharges. Both models predicted that fully reconnecting the seven side-channels would increase current N and P retention by 2–5 times, compensating for lower retention capacities in dry years. However, when related to the annual nutrient load of the Austrian Danube, reconnected side-channels account for a nutrient reduction of about only 0.1% (Natho et al. 2020). A subsequent larger-scaled modeling study concluded that Danube floodplains and the cumulative effects of restoration measures could indeed lead to measurable N-load reductions at basin scale (Tschikof et al. 2022).

scales as proposed in the "WETSCAPES" approach (Jurasinski et al. 2020). The EU-Restoration Law, aiming to restore 30% of all habitats listed in the FFH-directive annex 1 by 2030, offers an important vehicle for planning and implementing large-scale wetland restoration. However, though there are different planning tools already available the restoration potential of floodplains and wetlands is slowed down by conflicts of objectives, debates on financing, land availability, and its ecological potential (Harms et al. 2018). Applied research and the comprehensive interpretation of existing research is urgently needed to address the European-wide questions about the extent of relevant habitats, those in poor condition, and those suitable for restoration, particularly in the context of climate change.

In parallel, further improving our understanding of the mechanisms behind nutrient removal in wetlands and addressing challenges posed by anthropogenic pressures will help safeguard these ecosystems. This will ensure their continued ability to support biodiversity, water quality, and resilience in the face of global environmental changes. Specifically, we would suggest the following five research avenues:

Box 4. From measurement to management: Empirically derived proxies for floodplain N retention.

Figures: Left: German study sites contributing to the development of the proxy-based approach described below. Right: One of the six study sites (green dot) with an enlarged retention area during a flood event on the Elbe River due to dike opening © André Künzelmann, UFZ.

Self-purification, a key ecosystem service in wetlands, includes nitrogen (N) retention. In river-floodplain systems, N retention depends on both the N load of the river and the retention capacity of the river and floodplain. Nitrogen retention in floodplains can be quantified using deterministic models (see Box 3) or empirically:

The empirical approach focused on determining N retention proxies based on correlations between soil N retention rates and environmental factors. For this purpose, the soil denitrification potential of six floodplain areas along four large German rivers and the influence of hydrological and soil parameters were analyzed (Kaden et al. 2021). Soil pH was found to be the most important factor influencing potential soil denitrification rates, with greater potential observed in soils with pH > 7. Upscaling these estimates by incorporating modeled average inundation duration (Kaden 2022) was another critical factor in estimating potential annual denitrification rates.

The results of these model- and measurement-based data contributed to refining existing proxies of a German-wide proxy-based approach (PBA) on N retention in floodplains (Kaden et al. 2023b).

This enables estimating denitrification potential for entire rivers, as demonstrated for the Elbe and Rhine (Kaden et al. 2023b), and for smaller-scale assessments, such as evaluating the impact of dike relocations.

While model-based approaches may capture the complexity of denitrification drivers more effectively, this empirical method offers easily accessible and user-friendly data, supporting a comprehensive assessment of ecosystem services. It can inform decision-makers in prioritizing floodplain restoration measures and can be integrated into broader ecosystem service frameworks. One such framework is the River Ecosystem Service Index (RESI), which quantifies N retention and other ecosystem services in river-floodplain systems (Podschun et al. 2018). As a national prioritization approach, RESI allows for large-scale assessments of floodplain ecosystems, supporting the development of coherent river-floodplain management plans that prioritize restoration and enhance multifunctionality.

Similarly, a proxy-based approach for phosphorus retention is available (see Schulz-Zunkel et al. 2021).

1. **Examine wetland resilience to environmental changes:** Research should focus on the resilience of wetlands to shifting environmental conditions, particularly changes in hydrology, plant community dynamics, and the effects of climate-driven stressors on microbial functions. Additionally, studies should explore potential feedback mechanisms where disruptions to nutrient removal processes may exacerbate eutrophication or increase greenhouse gas emissions.
2. **Develop cost-effective, scalable monitoring techniques (Cvijanović et al. 2026):** Efforts should be made to develop affordable, standardized, comparable and scalable monitoring methods – combining field surveys, in-situ nutrient measurements and remote sensing– to assess restoration success and identify areas requiring further intervention. Monitoring should also track water quality improvements, biodiversity changes, and reductions in nutrient pollution in adjacent water bodies.

3. **Create simulation models to predict hydrological impacts:** Develop simulation models to predict how changes in hydrological patterns will affect nutrient removal and overall wetland functionality. Efforts should build on existing models and integrate field data, remote sensing, and climate information to improve accuracy. These models should be calibrated and validated with empirical data, provide insights into potential disruptions, and guide adaptive management strategies for wetland restoration.
4. **Investigate microbial ecology and nutrient cycling:** Research should focus on further developing existing methods to identify key microbial communities involved in N and P removal in wetlands. Studies on plant-microbe interactions are essential to understand how plants foster microbial communities that enhance nutrient cycling. Genomic and metagenomic analyses are also crucial for exploring microbial diversity and their functional traits in nutrient transformation processes in wetland ecosystems.
5. **Promote cross-disciplinary collaboration:** Further strengthen collaboration across disciplines – hydrology, ecology, and socio-economics – to build integrated approaches for wetland management and restoration. A holistic perspective that includes nutrient cycling is necessary to address the complex challenges facing wetland ecosystems and to inform policy and management decisions.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Dominik Zak and Ute Susanne Kaden conceptualized and developed the overarching framework for the review. Dominik Zak wrote the original draft, and all authors contributed substantially to the writing and revision of the manuscript. Miaorun Wang, Martin Tschikof, Brian Kronvang, Stephanie Natho, and Ute Susanne Kaden were primarily responsible for drafting the case study boxes.

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Data availability

All of the data that support the findings of this study are available in the main text.

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