The role of seagrass meadows in nitrogen cycling and coastal water purification

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Abstract

Seagrass meadows serve critical roles in the coastal ecosystem by providing ecosystem services such as nitrogen cycling and water filtration. On top of this, these 'underwater grasslands' help mitigate problems associated with excess nitrogen surpluses in coastal waters such as eutrophication and harmful algal blooms. This paper analyzes the impacts of seagrasses on the nitrogen cycle, including nitrogen uptake, assimilation, denitrification, and sediment stabilization. In addition, this paper discusses the role of seagrasses in the prevention of eutrophication and their improvements towards water quality as well as their overall ecosystem service value. Understanding these processes is essential for the sustainable conservation of coastal ecosystems and water quality management.

Keywords: Seagrass, Meadows, Coastal ecosystems, Nitrogen, Denitrification, and Eutrophication

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Introduction

Seagrass meadows, shallow underwater ecosystems in marine water and estuaries, are highly intricate and ecologically valuable zones. These undersea plants thrive around the coastline forming prairies which offer a number of ecological services such as habitat formation for marine fauna, sequestration of carbon dioxide, stabilization of sediments, and enhancement of water quality. One of the major contributions is the nutrient recycling, particularly of nitrogen, coastal ecosystems need to be healthy (Collier *et al.*, 2011). As coastal areas deal with escalating nutrient pollution as a consequence of human action, it is indispensable for ecosystem-based governance and management approaches to understand the roles seagrass meadows play in nitrogen recycling and coastal waters purification. In addition, further research aimed at estimating the potential for nitrogen removal in these critical habitats could provide vital data for mitigating non-point anthropogenic nitrogen pollution in sensitive coastal waters (Vermaat, 1993; Salman, Al-Noor and Khalaf, 2024).

Plankton, seaweeds, and sea grasses as primary producers in an ecosystem biosphere require nitrogen to grow (Duarte, 2014; CSLJRC *et al.*, 2013). The disruption happens when farming drainage and industrial waste provide surplus nitrogen through runoff and deposition (Silva *et al.*, 2017). The ecological destruction of the coastal environments, such as eutrophication, hypoxic dead zones, and harmful algal blooms, which undermine water quality, biodiversity, and the coastal ecosystems' steady state, occurs (Wolf, 2013). During the eutrophication stage of the process, explosive algal growth from nitrogen supersaturation occurs, which results in the depletion of available light and oxygen (McGlathery *et al.*, 2010). The increase in nutrient pollution accelerates the demise of seagrass meadows as oxygen levels drop (Meisner *et al.*, 2019). Hence, vigilance of nitrogen levels in surrounding seas is pivotal to sustaining ecosystem health and resilience against human-induced disturbances (Heffernan *et al.*, 2017; McDonald *et al.*, 2015).

Specifically Zostera marina, Posidonia oceanica, and Thalassia testudinum, a type of seagrass, have the ability to mitigate nitrogen pollution owing to their transformation skills and absorption capacities (McDonald *et al.*, 2008; McDonald *et al.*, 2015). They transform and absorb nitrogen in the form of ammonium, nitrate, or even in a dissolved organic state from both water and the sediment. This diminishes the total concentration of nitrogen in the water bodies, avoiding numerous detrimental associated impacts with nutrient loading such as algal blooming. Seagrass also facilitates accelerated microbial metabolism denitrification which surplus nitrogen as nitrogen gas and breathes it out into the atmosphere, thereby "removing" it from the ecosystem (Carruthers *et al.*, 2007; Sharma and Iyer, 2023).

The nitrogen secondary uptake influences sediment interaction, which does not include direct nitrogen uptake. Seagrasses meadows have the ability to trap water, which in turn slows down its movement, resulting in the greater deposition of suspended particulate matters which include nitrogenous organic matters. This also aids in the release of organic exudates from the roots of seagrass which aid in sustaining the microbial communities that perform nitrogen transformations. As a consequence, seagrass meadows continue to function as natural water quality improvement polishes, buffering nitrogen-dominated sediments and facilitating microbial transformations of nitrogen to non-reactive forms (Van Tussenbroek, 2008) and (Kaul and Prasad, 2024).

Seagrass meadows are crucial for the coastal ecosystem, as they aid in improving water quality through nitrogen cycling. Therefore, their conservation and restoration are necessary. However, coastal human development, pollution, climate change and other human induced activities pose a serious threat to seagrass habitats (FTSMLKL *et al.,* 2013). The loss of seagrass meadows has further increased nitrogen pollution alongside diminishing the ecosystem's ability to self-clean. These factors have created an immediate need for active protection and restoration efforts in order not to lose these fundamental ecosystems (Fortes, 2014; Pernul and Fuchs, 2010).

This paper seeks to investigate the role seagrass meadows play in the coastal waters nitrogen cycle, specifically detailing the processes of nitrogen uptake, transformation, and removal. The study concentrates on the removal processes of nitrogen in seagrass ecosystems which includes incorporation, denitrification, and burial in sediments (Adams *et al.,* 2017). Moreover, the paper addresses the possible benefits of conservation and restoration of seagrass with respect to nitrogen pollution and advocates integrated coastal management approaches which emphasize the primary multifunctional value of seagrass meadows (Jarvis *et al.,* 2016; BKS ACT *et al.,* 2017).

Seagrass Meadows and Nitrogen Cycling

Directly and indirectly, seagrasses have a direct influence on nitrogen cycling. Through natural processes and human activity, the coastal ecosystems assimilate nitrogen in the form of ammonium (NH_4^+), nitrate (NO_3^-), and organic nitrogen compounds. Once in coastal waters, Seagrass meadows help contain and regulate the availability of nitrogen, thereby preventing excessive surplus that can be harmful to the environment, enabling the mitigation of excess in figure 1.

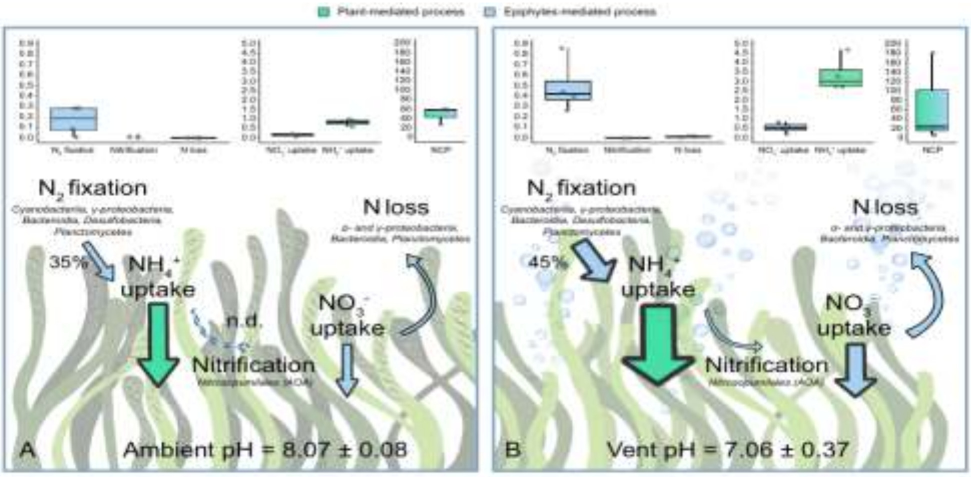

Figure 1: An Overview of Nitrogen Cycling Processes Under Ambient and Ventilated pH Conditions.

Nitrogen Uptake and Assimilation

Seagrasses predominantly soak up nitrogen from their surroundings via the roots and leaves. Roots are particularly effective in capturing nitrogen in ammonium form, which is plentiful in pore water within sediments. Seagrasses have evolved to capture and store nitrogen in tissue as ammonium, especially useful in areas devoid of nutrients. Besides ammonium uptake, seagrasses take nitrate from the water column through their leaves. The absorption process is more multifaceted biochemically, where nitrogen is transformed into organic substances requisite for the growth and development of seagrass plants, such as amino acids and proteins in figure 2.

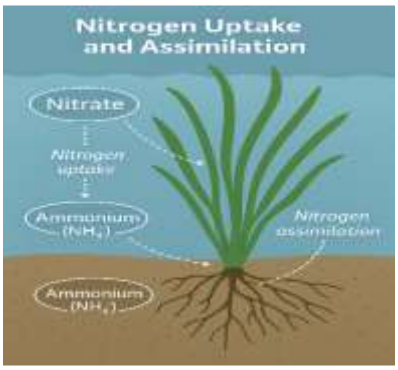

Figure 2: Nitrogen cycling in seagrass meadows

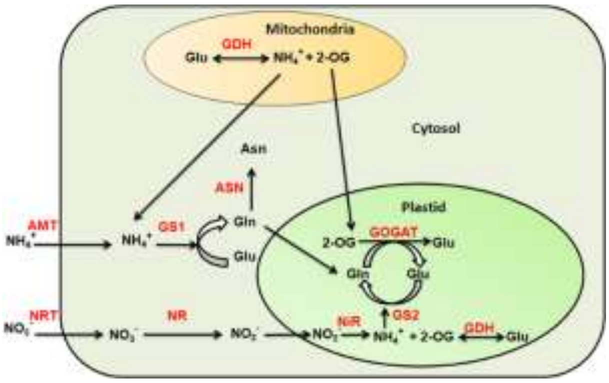

Figure 3: Nitrogen uptake and assimilation process in seagrass

The nitrogen absorbed by seagrasses sustains a plant's metabolism, facilitates growth, and adds to the biomass of the seagrass meadow in figure 3. Nutrient assimilation also enhances the ecological quality of the water body by lowering the concentration of nitrogenous compounds, which, in excess, can lead to eutrophication, thus limiting nutrient-infested algal blooms. Seagrasses efficiently and rapidly assimilate nitrogen and are key to reducing coastal waters' nitrogen pollution.

Denitrification

Denitrification refers to the biological process by certain microorganisms in which energetically favorable reduction of nitrate (NO_3^-) occurs to produce nitrogen gas (N_2) that is released back to the atmosphere. This process usually takes place in the absence of oxygen (anoxic) environments, where denitrifying bacteria utilize nitrate as an electron acceptor. Seagrass meadows offer a unique example of a denitrification ecosystem because of their roots. The oxygen released by the seagrass roots into the surrounding sediment form redox gradients supporting nitrification (oxidation of ammonium to nitrate) in the upper sediment layers and denitrification in deeper anoxic layers.

Seagrass growth leads to sediment oxygenation around the roots that allows for vertical spatial separation of nitrification and denitrification processes enhancing the efficiency of nitrogen removal in the sediments. Therefore, seagrass meadows serve as natural buffering systems that efficiently strip nitrogen from water in the form of gas, preventing harmful impacts associated with its excess accumulation such as hypoxia or algal blooms.

Sediment Stabilization and Nitrogen Burial

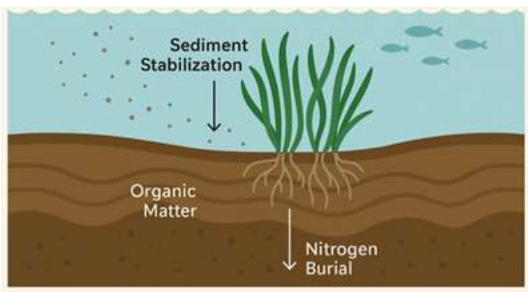

Figure 4: Sediment Stabilization and Nitrogen Burial

Sedimentary stabilization occurs due to Seagrass meadows anchoring the seabed with their dense root systems in figure 4. This helps in sedimentation as protective coarse beds act as consolidated and stagnant gas-rich layers. The permeable block also acts to resists the re-suspension of particulate matter rich in nitrogen components which augments sediment resuspension. Also, if nitrogen components are bound to sediment, the porous medium will aid in less re-release to water column thus restricting nitrogen enrichments.

Also, the incorporation of nitrogen into seagrasses's biomass enables the meadows to contribute to nitrogen burial. This can later be rendered as a result of the death and subsequent decomposition of seagrasses rendering organic material in the sediment. This serves as long term storage of nitrogen as it precludes the cycling of nitrogen back to the water column. Keeping buried nitrogen also assist in the balance of the nitrogen cycle because it prevents excess nitrogen from coastal waters.

Seagrasses and Eutrophication Prevention

The over-intensification of water bodies with nourishing nutrients particularly nitrogen and phosphorus also referred to as Eutrophication. Seagrass meadows help prevent this phenomenon by regulating nitrogen levels while promoting better water condition.

Reduction of Algal Blooms

Algal blooms, a potential threat to marine life, are associated with excess nitrogen from coastal areas, which consumes oxygen and blocks sunlight. Eutrophication, in its extreme form, leads to harmful algal blooms (HABs) that decimate marine fauna and degrade water quality. Seagrasses alleviate water pollution as the underwater grasslands within coastal regions act as nitrogen sinks and decelerators of nitrogen-rich wastewater. Often, water bodies that have productive seagrass meadows experience alleviated moderate to severe algal blooms compared to regions without seagrasses. The meadows enhance the regions' phytoplankton and phytosynthetic biomass, consequently enabling enhanced Light Attenuation and mitigating replenishment of Nitrogen thus hindering phytoplankton, algae, and HABs from occurring. Measured concentrations of different ocean nutrients during the summer months validate regional water quality improvement assertions in figure 5.

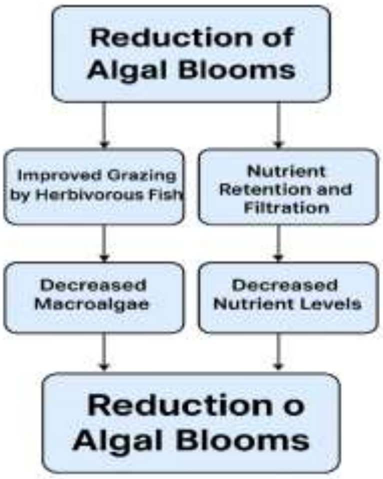

Figure 5: Reduction of Algal Blooms for Seagrass and Eutrophication Prevention

Moreover, seagrass meadows serve as a buffer zone of physical habitat that harbors grazers and detritivores and other species that feed on nitrogen-rich algal blooms. The two processes combined assist in controlling algal growth and augmenting the efficacy of seagrasses in managing water quality.

Enhancing Water Clarity

Seagrass meadows improve water clarity by stabilizing sediments, which avoids resuspension. This is critical in areas where sediments contain nitrogen and other nutrients. By regulating nutrient release into the water column, seagrasses aid in nutrient-rich waters, which support the growth of other marine flora and improve ecosystem health. Other marine life also benefits from improved water visibility because deeper water light provides the growth of benthic algae and other photoautotrophs, strengthening ecosystem diversity and productivity.

Ecosystem Services Extended by Seagrasses

Besides the nitrogen cycle, seagrass meadows provide critical ecosystem services that maintain the health of the region. These services are vital to ecological well-being, carbon sequestration, resilience of the coast, and human health in figure 6.

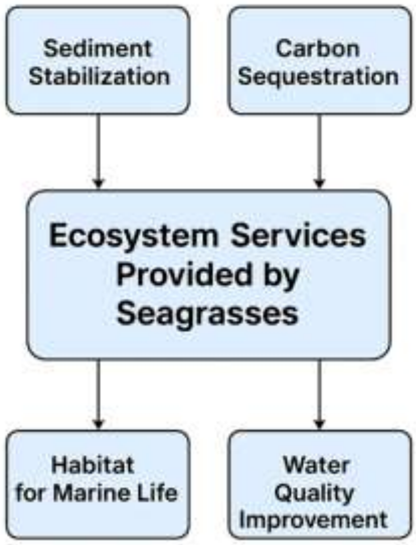

Figure 6: Ecosystem services by Seagrass

Carbon Sequestration

Seagrasses have the important capability of fighting climate change as an ecosystem which captures and stores carbon. Carbon is sequestered in vegetation as well as in the sediments beneath. The organic carbon captured in seagrass meadows is less likely to be released as carbon dioxide and is more likely to be entombed within sediments for centuries. Hence, seagrass meadows are emerging as some of the most efficient ecosystems in carbon sequestration, and in some cases, even surpass tropical forests. The global carbon management policies introduced latterly have provided greater focus on seagrass ecosystems and their ability to store and sequester carbon.

Habitat for Marine Life

Many species such as juvenile fish, invertebrates, and crustaceans use the seagrass meadows as critical nurseries and habitats. The adult population members also depend on the seagrass meadows for food as well as shelter. The diverse benthic features of seagrass meadows provide refuge for numerous organisms which helps in predation, feeding, breeding, and sheltering as well. These seagrasses support unparalleled biodiversity because they nourish and are a source of food and shelter for many organisms like large fish and invertebrates. Increased biological diversity improves the productivity and cohesiveness of coastal ecosystems.

Coastal Défense and Erosion Control

Seagrass meadows mitigate wave energy and hold sediments in place capturing submerged debris, helping to prevent coastal land erosion. Seagrasses literally act as walls to waves, aiding in sediment retention and diminishing coastline erosion. This becomes of particular importance in areas where socio-economic aggressions and natural systems interlace with tidal and coastal land erosion threats. In addition, seagrass meadows assist to mitigate impacts from storm surges, elevated seas, and other meteorological shifts, acting as natural protective barriers. Seagrasses help restore coastal habitat and bolster coastal communities' resilience by reducing erosion.

Conclusion

The seagrass meadows assist in the nitrogen cycling of a region’s coastal ecosystems and also aid in purifying the ecosystems. Most importantly, it also contributes to the overall health of the coastal waters of the region. Seagrass meadows supress coastal eutrophication and maintain water quality, in addition to mitigating excess nitrogen impacts in coastal waters from nitrogen uptake, assimilation, denitrification, and sediment stabilization. Furthermore, seagrasses help fenestrate ecosystems by capturing carbon gases, protecting the coast, sustaining crucial habitats, and thus aids in the resilience of fenestrate ecosystems. Hence, preserving and restoring coastal ecosystems in turn provides life for the people and animals, protecting the ecosystem from additional damages.

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