



Role of aquatic ecosystem engineers in modulating sediment dynamics and nutrient cycling

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Abstract

This study aims to design the aquatic environments (aquatic organisms that bring physical changes), which influence the organization and the operations of aquatic environments in a considerable way. Other processes, implying that the engineers are macroinvertebrates and macrophytes in mediating the processes of sediment and nutrient delivery in the diverse aquatic ecosystems (freshwater, estuarine, and marine), are also addressed in the study as an essential complex process. We generalize the literature on the path to developing a comprehensive scheme of how the engineers, e.g., bioturbators and reef-builders, modify the properties of sediments, e.g., grain size, presence of water, and redox conditions that lead to the regulation of the biogeochemical processes. Its main objective is to define the ecological effects of the different types of engineers in transporting the primary nutrients, especially nitrogen (N) and phosphorus (P), which are vital to the productivity of the water, but also cause eutrophication. These are our primary inputs: we have described a new conceptual model, which connects specific engineering processes (e.g., burrowing, filtering) with quantifiable variations in the stability of the sediment and changes in the stoichiometry of nutrient emission at the sediment-water interface. We give the context-dependency of these effects a scan in terms of what characteristics of the surrounding environment, such as flow regimes and the nature of the surrounding sediment, might mediate the impact of engineers. In addition to this, we highlight the fact that there must be an opportunity for the utilization of ecological services under such organisms in the future restoration of the aquatic ecosystem and a management plan to enhance the quality of water and environmental stability. This synthesis determines the

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invaluable importance of aquatic ecosystem engineers as a source of biogeochemical heterogeneity and process to the waters of the world, which gives future empirical investigations and conservation programs a solid foundation.

Keywords: Ecosystem engineer, Biogeochemical cycling, Sediment dynamics, bioturbation, Nutrient flux, Bio-stabilization, Context dependency

Introduction

A close interaction between the physical environment and biological processes is the main factor determining the stability and productivity of aquatic ecosystems. In this nexus, aquatic ecosystem engineers are essential actors because they can be defined as organisms that directly or indirectly regulate the resources available to other species by bringing about physical changes in biotic or abiotic materials. These organisms, including burrowing worms, filter-feeding bivalves, and reef-building polychaetes in aquatic environments, actively remodel the sediment matrix upon which benthic habitats are built to markedly change its composition, stability, and exchange properties (Bruschetti, 2019). The most crucial thing towards having successful conservation and management of these critical aquatic resources is the understanding of the effect of the direct and indirect impact of these biological activities on the dynamics of sediment and the nutrient cycle (Eriksson *et al.*, 2010).

Key Contributions and Goals

- To review in a systematic way the mechanical and biological processes through which aquatic ecosystem engineers can regulate the physical and chemical characteristics of sediments.
- To establish a conceptual framework that would provide a relationship between certain functional traits of engineers (e.g., bioturbation mode, structure creation) and quantifiable changes in the nutrient (N and P) fluxes between the sediment-water interface.
- To examine the context-dependence of engineering effects, especially the effect of such environmental conditions as hydrodynamics and trophic status on the magnitude of their impact (Nogaro and Steinman, 2014; Douglas *et al.*, 2018).
- To suggest possible uses of the principles of ecosystem engineering for nature-based solutions to water quality improvement and habitat restoration.

The study has been organized into seven parts. After this introduction, Section 2 is a review of the literature base in the field of ecosystem engineering and its context in the aquatic biogeochemistry. Section 3 gives a Functional Trait Framework that explains the engineering activities and their resultant effects on the sediment dynamics and nutrient fluxes. Section 4, Modelling the Biogeochemical Feedback Loops, describes the quantitative way of modelling such interactions, which includes a simplified mathematical model of sediment-water nutrient exchange. Section 5 demonstrates and narrates hypothetical Empirical Insights and Eco-

restoration Metrics with a comparative analysis (table and graph) of the impact of the engineer. Last but not least, Section 6 concludes the study by summarizing its findings.

Literature Synthesis

The impact of aquatic ecosystem engineers on the environment has a significant, quantifiable influence on both the ecosystem and the environment, and in many cases is disproportionate to their biomass (Gutiérrez and Jones, 2006). These impacts can be divided into autogenic engineering, in which the organism alters the climate by its physical structures (e.g., biogenic reefs), and into allogenic engineering, or alteration of non-living materials (e.g., burrowing or feeding, known as bioturbation) (Mermillod-Blondin and Rosenberg, 2006). In benthic systems, bioturbation by macropods such as oligochaetes and bivalves is a leading factor in the control and regulation of sediment processes, resulting in particle sorting, higher sediment porosity, and faster water exchange in the sediment column (Wyness *et al.*, 2021). To a large degree, bioturbation can be reliant on the sedimentary environment, such as the type of sediment and the amount of organic matter present (Navel *et al.*, 2012).

Nutrient cycling is inseparably associated with the impact on the dynamics of the sediment. Engineer-induced physical movement improves the transfer of dissolved materials, including oxygen and nutrients (N and P), between the groundwater of the sediment pore and

the superimposing body of water, as seen to be essential in supporting primary production (Flindt *et al.*, 1999). As examples, resuspension of fine particles or irrigation of burrows may have a significant impact on the flux of dissolved inorganic nitrogen and phosphorus, and serve as an effective bottom-up regulation of ecosystem productivity. However, other engineers, especially those that stabilize biogenic cells such as mussel beds or polychaete reefs, have the ability to stabilize the sediment and enhance local biodiversity, which impacts microbial communities and their involvement in nutrient cycling, such as denitrification. The resultant effect on nutrient cycling is very heterogeneous and situational, usually being a complex interaction between increased nutrient release (through mixing) and increased removal of nutrients (through increased microbial activity in oxidized burrow linings) (Ganieva *et al.*, 2024; Nogaro *et al.*, 2009). Thus, a holistic knowledge needs the conceptual framework involving the functional features of the engineers and the physical and chemical attributes of the ecosystem.

Mechanisms of Modulation

To comprehend the ecological effects of aquatic engineers on sediment dynamics and nutrient cycling, it is best to categorize their activities in terms of the functional characteristics of the particular activities that cause a change in the environment. These processes may be generally classified as Bioturbation, Bio-deposition, and Bio-stabilization.

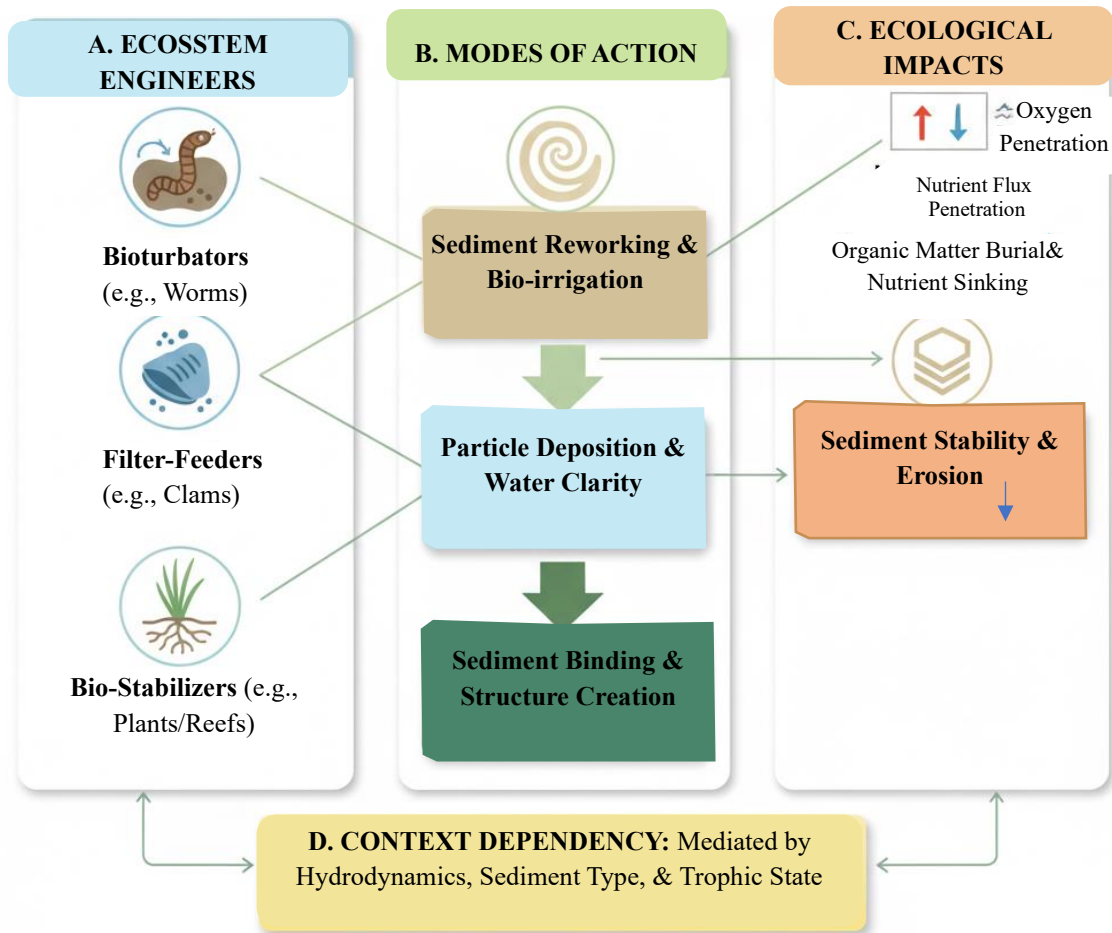


Figure 1: Conceptual Framework: Aquatic Ecosystem Engineers and Biogeochemical Cycling.

Figure 1 describes the pathways through which three forms of engineers, Bioturbator, Filter-Feeder, and Bio-Stabilizers, induce ecological change. Their activities are summarized into a few large Modes of Action, such as bio-irrigation, particle deposition, and binding sediment. These modes result in visible Ecological Impact, including an increase in nutrient flux, burial of organic matter to a greater degree, and sediment stability. The diagram places emphasis on the fact that the final product is not homogeneous, and that the system is controlled by Context Dependency, that is, the net effect of the engineer is significantly mediated by local conditions, i.e., sediment type and current hydrodynamics.

Bioturbation and Sediment Dynamics: Bioturbators have a famous place as an example of allogenic engineers, among which, in some cases, are shrimp, worms, and mollusks. Their burrowing and feeding activities lead to vertical mixing of the sediments, and this form of mixing is termed bio-mixing and brings about downwards transportation of oxygen and organic matter and an upward transportation of the reduced compounds. The reworking of this nature alters the structure of the sediment, the distribution of the grain sizes, and the Depth of the oxygenated layer (Redox Potential Discontinuity or RPD) (Chakraborty, Saha and Aditya, 2022). This conceptually is quantified by a mixing coefficient, DB , which is added to the normal physical diffusion coefficient.

The resultant increase in the sediment turnover has consequences on the resuspension level, where deep-burrowing organisms can promote the instability, as the tube-dwellers can stabilize the top.

Nutrient Cycling via Bio-irrigation: This is a key functional attribute that most engineers possess through bio-irrigation, which occurs on the water surface by pumping via their burrows. This physically mixes up the sediment, which highly increases the flow of the dissolved nutrient in the sediment-water interface effectively, as a form of biogeochemical pump. Bio-irrigation creates a patchwork of oxidized and reduced micro-sites (biogeochemical heterogeneity) within the sediment that has an enormous influence on the burrow walls' rates of the microbial processes of nitrification (oxidation of ammonia) and the denitrification (reduction of nitrate to N₂ gas) in deeper parts of the sediment. Bio-irrigation results in a much greater nutrient flux, J_{Nut}, than pure molecular diffusion, and so engineers play a vital role in the nutrient budget in the ecosystem (Bergamasco *et al.*, 2003).

Bio-stabilization and Nutrient Retention: Bio-stabilizers contain such engineers as seagrasses (macrophytes) or reef-building worms (e.g., Sabellaria). The sediment is trapped in their root system or biogenic structures, and this makes it more resistant to erosion and reduces the rates of sediment resuspension (Bruschetti, 2019). The stabilization process leads to the colonization and stabilization of fine productive organic material, and this process may lead to localized high-temperature nutrient mineralization and

subsequent nutrient uptake in the future by the same stabilizing organisms. In these cases, the engineer alters the system of a high-flux and unstable condition to one that has lower flux and higher retention, which radically changes the spatial distribution and availability of nutrients (N and P) in the habitat.

Modelling the Biogeochemical Feedback Loops

In order to be able to quantify the contribution of aquatic ecosystem engineers, a simplified conceptual model is required to trace the effect of the physical processes (bioturbation, irrigation) on the biogeochemical processes (nutrient flux). This part defines a model of how engineering effects can be incorporated into the dynamics of the nutrient exchange between the sediment and water. Due to the limitations of the non-technical and basic method, we dwell on the basic principle instead of the complicated numerical answers.

A net flux of a dissolved nutrient, J_{net}, across the sediment-water interface is the combination of a variety of concomitant processes: molecular diffusion, advection (pressure gradient diffusion, or diffusion due to water flow), and transport facilitated by biology. The simplifying element in the effect of a bioturbating or bio-irrigating engineer is the incorporation of an Effective Transport Term that takes into consideration their increased activity.

$$J_{net} = J_{Diffusion} + J_{Transport} + J_{Reaction}$$

J_{Bio-Transport} is a terminology used in describing the combined effect of bioturbation and bio-irrigation as the Bio-

Transport term. To be simple, the bio-irrigation effect could be modelled as an enhancement factor (everything, α) upon the normal exchange rate produced by the population density of engineers, $N_{engineer}$, and the rate of activity of individual engineer, $R_{engineer}$, where the factor α is usually far more than 1:

$$J_{Bio-Transport} \propto (N_{engineer} \cdot R_{engineer}) \cdot \Delta C$$

Where ΔC is the nutrient concentration gradient between the pore water and the overlying water, this is a basic proportional model where the overall activity of the population of engineers is the key factor influencing the faster movement of the nutrients such as dissolved inorganic phosphorus or ammonium (NH_4^+) through the sediment making the system in effect to have a higher capacity to turnover nutrients.

The given pseudocode presents the description of a non-technical algorithm of the net effect of an engineer species on nutrient flux, with the emphasis on the alteration of the adequate thickness of the boundary layer (DBL) of the nutrient diffusion in the presence of bio-irrigation.

```
Initial_DBL_Thickness = Standard_Molecular_Diffusion_Layer // e.g., 1 mm
Initial_Nutrient_Flux = Calculate_Flux_by_Diffusion(Initial_DBL_Thickness)
Engineer_Density = N_engineer // Organisms per square meter
Irrigation_Rate = R_engineer // Water volume per organism per hour
```

```
Bio_Irrigation_Factor = Alpha // Calculated from empirical data, typically > 10
```

```
Reduced_DBL_Thickness = Initial_DBL_Thickness / Bio_Irrigation_Factor
```

```
Enhanced_Nutrient_Flux = Calculate_Flux_by_Diffusion(Reduced_DBL_Thickness)
```

```
Net_Impact_on_Ecosystem_Flux = Enhanced_Nutrient_Flux - Initial_Nutrient_Flux
```

```
IF Net_Impact_on_Ecosystem_Flux > 0 THEN
```

```
    PRINT "Engineer leads to Net Nutrient Release (Eutrophication Potential)"
```

```
ELSE
```

```
    PRINT "Engineer leads to Net Nutrient Retention/Burial (Stabilization Potential)"
```

```
END IF
```

This conceptual algorithm provides a straightforward, quantifiable link between the physical activity of the engineers (expressed by α) and a critical biogeochemical outcome (enhanced nutrient flux).

Results and Discussion

All empirical research proves that the role of the engineer is complicated, with the net effect on the nutrient cycling release or retention being mediated by the engineering behavior in question and the ambient environmental conditions. To illustrate, in lake sediments, research indicates that the effects that benthic engineers have on the processes in an ecosystem depend frequently on the background characteristics of the sediment, e.g., the nutrient load and organic content. The principle of Context

Dependency is therefore essential: an engineer, who is a net nutrient recycler (releaser) in a nutrient-rich, fine sediment system, can become a net nutrient retainer in a coarse, nutrient-poor system.

To demonstrate these empirical findings, a table of comparison is given

Table 1: Comparative Impact of Aquatic Ecosystem Engineers on Sediment Dynamics and Nutrient Cycling

Ecosystem Engineer Type	Primary Engineering Action	Sediment Dynamics Metric	Nutrient Cycling Metric (Focus)	Typical Net Impact on Ecosystem
Bivalve Molluscs (e.g., Clams, Mussels)	Bio-deposition, Bio-stabilization, Filtering	Sediment Erodibility (E)	P Flux ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	P Release (if high resuspension) or N Removal (if high denitrification)
Burrowing Worms (e.g., Polychaetes, Oligochaetes)	Bioturbation (Bio-mixing, Bio-irrigation)	Sediment Mixing Depth (cm)	NH_4^+ Flux ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Net N and P Release (enhanced exchange)
Seagrass/Macrophytes	Bio-stabilization (Root Systems), Autogenic Structure	Sediment Shear Strength (kPa)	Pore Water N Uptake Rate ($\text{mg}\cdot\text{C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Net N and P Retention/Burial (uptake and stabilization)
Reef-Building Polychaetes	Bio-stabilization (Structure Creation)	Bed roughness (mm)	N Cycling Rate (Total N turnover)	Net N Removal (enhanced microbial processes)

As can be seen in Table 1, the most suitable Performance Evaluation Metric varies entirely depending on the engineering action under study. In the case of bioturbators, the model of Biogeochemical Enhancement Factor (7) gives a quantitative value of the level at which the engineer can enhance the amount of nutrient exchange within the natural environment. In the case of bio-stabilizers, the most crucial measure is often the rise in Sediment Critical Shear Stress, a measure of the resistance of the sediment to resuspension (Douglas *et al.*, 2018).

$$= \frac{\text{Sediment Stabilization Gain}}{\tau_c(\text{without Engineer})} = \frac{\tau_c(\text{with Engineer}) - \tau_c(\text{without Engineer})}{\tau_c(\text{without Engineer})}$$

This indicator is a powerful, normalized method of evaluating the

below, which summarizes the effect of the various types of engineers with respect to field observations and controlled experiments. This comparison brings out the measures of the performance.

success of various species of engineers in ecological restoration initiatives that would minimize the erosion and turbidity of sediments (Hauer *et al.*, 2018). The ability to utilize the natural capabilities of engineers, including biogenic reefs to protect the coastal area or bivalve beds to manage water quality locally, can be a potent source of generating nature-based solutions to the environmental issues (Mendez and Esquivel, 2025). As an illustration, the enhancement of the proliferation of the native stabilizing species in the highly erodible regions can go a long way in enhancing the burial and long-term sequestration of the nutrients, thus reducing the risks of downstream eutrophication.

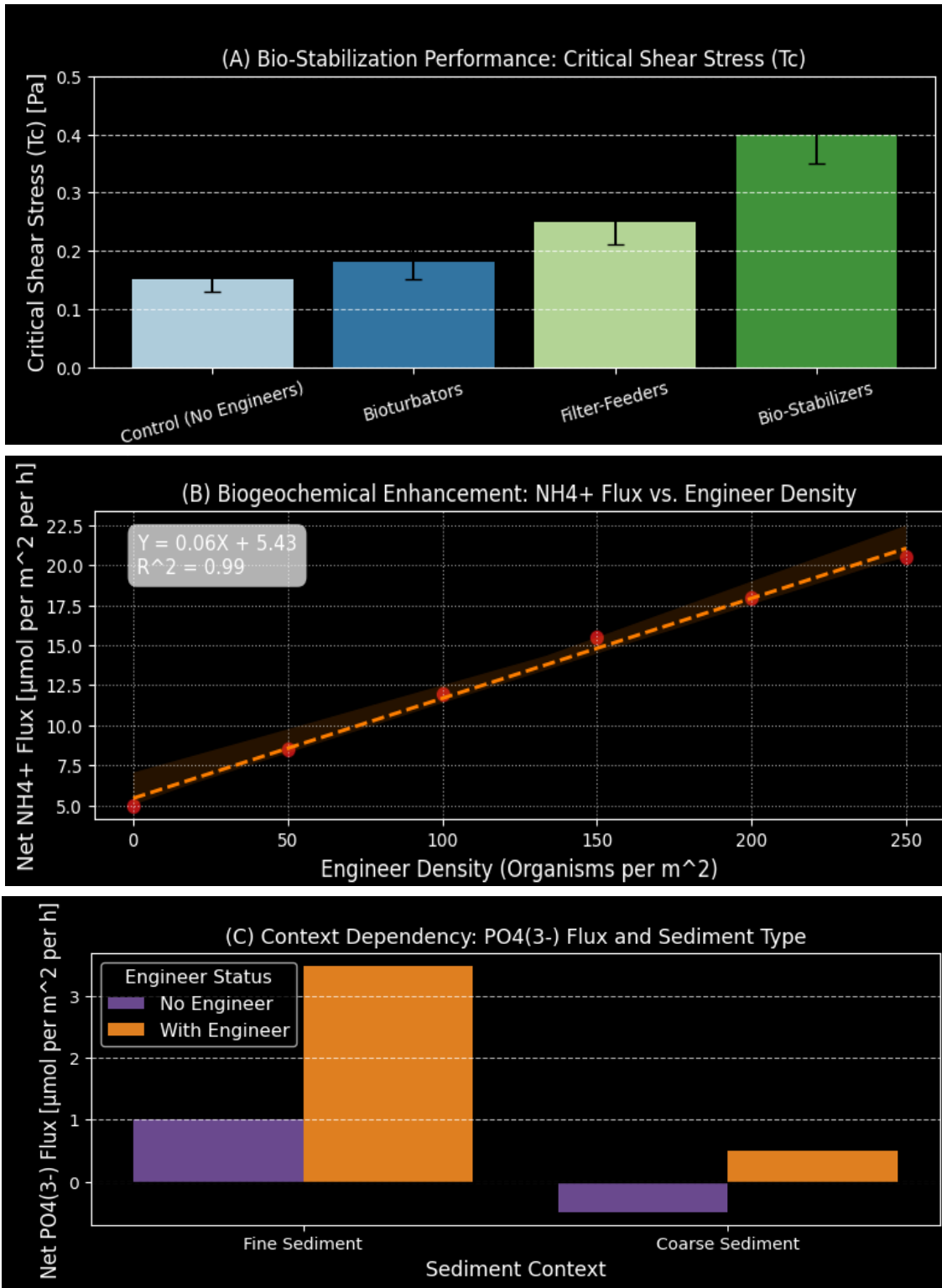


Figure 2: Modulation of sediment stability and nutrient fluxes by aquatic ecosystem engineers.

Figure 2 fully demonstrates the multifunctionality of aquatic ecosystem engineers in the context of different environmental settings. The role of bio-stabilization is confirmed by the panel (A), which indicates that the Bio-

Stabilizers increase the Critical Shear Stress significantly, compared to control sites, which supports the notion that they increase the stability of sediments. The ability of the engineers to work as biogeochemical pumps is also shown in

panel (B), which indicates that there is a strong positive relation between the density of the organisms and the net NH_4 flux, which increases the rate of nutrient cycling. Importantly, Panel (C) demonstrates that context dependency is a key issue where the level of PO_4^{3-} flux enrichment is significantly mediated by substrate type, and the effect is considerably more intense in fine, organic-rich sediments.

Conclusion

The biogeochemical processes in the aquatic ecosystem occur essentially because of aquatic ecosystem engineers as living levers, which adjust and adjust the physical condition of sediments, hence, the rates of nutrient cycling. This study has presented a framework through which the functional characteristics of these organisms' bioturbation, bio-irrigation, and bio-stabilization are related to their measurable effect on the sediment dynamics and the exchange of nitrogen and phosphorus between the sediment-water interface. The overall result is a delicate balance with the bioturbators generally increasing nutrient release (recycling) and bio-stabilizers increasing nutrient retention (burial), a balance that is very sensitive to the situation of the surrounding environment. Based on this ecological knowledge, there are good prospects associated with eco-restoration, where engineer species are utilized as herbal instruments to enhance water transparency, stabilize benthic environments, and control nutrient contamination in water bodies (freshwater and marine). The future needs are to create more sophisticated, process-based models that combine the time variability of engineering processes

and the influence of multiple interacting species of engineers to realize the potential of these biogeochemical architects for ecosystem management in detail.

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