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Ecological Responses of Intertidal Microalgal Communities to Repeated Freshwater Inundation

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Abstract: Intertidal ecosystems are characterized by frequent environmental changes caused by tidal dynamics, precipitation, river runoff, and coastal hydrology. Frequent inundations of fresh water constitute one of the environmental disturbances that change salinity, nutrient status, sediments, and physiological processes affecting the intertidal microalgae. Intertidal microalgal communities, especially benthic diatoms, play an important role in primary production, nutrient recycling, sediments stabilization, and energy flows in coastal ecosystems. The present conceptual study attempts to identify the possible ecological reactions of intertidal microalgal communities to repeated flooding by integrating hydrologic disturbance, physiological adaptation, community reorganization, and ecosystem function into one framework. Inundation frequency, duration, intensity, and recovery periods are recognized as main environmental factors affecting community reactions. Osmoregulation, salinity tolerance of individual taxa, community structure, functional diversity, photosynthesis, and microbiological interactions are all emphasized. The theoretical model suggests that the continuous flooding with freshwater may lead to various effects based on the level of disturbance frequency, salt content of the ecosystem, nature of sediments, availability of nutrients, and adaptation mechanisms in microalgae. In addition, the conceptual framework emphasizes the value of making a distinction between short-term physiological response and long-term community reorganization. The framework serves as a basis for future experimental work and the development of microalgal indicators for hydrological disturbances.

Keywords: Intertidal Ecosystems; Microalgal Communities; Freshwater Inundation; Microphytobenthos; Salinity Fluctuations; Ecological Resilience.

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I. Introduction

Intertidal ecosystems are examples of dynamic coastal zones that experience periodic submersion and exposure due to tidal action. In such ecosystems, microbial communities play an important role in the process of primary production, nutrient turnover, sediment stabilization, and interactions within the ecosystem. The biological components found in intertidal ecosystems include microphytobenthos communities that inhabit the sediments where microalgae, including diatoms and cyanobacteria, among others, can be found. These microorganisms are not only important for the process of primary production but also due to the extracellular polymeric substances they produce.

Conditions within intertidal systems are highly variable over relatively short time periods. Conditions such as salinity, temperature, irradiance, nutrient content, water content, and sediment moisture control the growth and structure of microalgae communities. Freshwater flows into the system due to precipitation, river flow, drainage, and coastal runoff represent further hydrological disturbance. These disturbances lead to a fast decrease of salinity in the pore water and changes in the chemical environment around microorganisms that live within the sediments. The extent of change depends on the amount of freshwater in the system, the time of exposure, tidal flow, and properties of the sediments themselves. Hydrological disturbance is an important environmental pressure on freshwaters (Reid et al., 2019).

The effect of freshwater inundations on the ecology of the ecosystem is highly significant because there are additional ecological impacts of repeated inundations, which are not caused by each single event. Multiple disturbances might affect the ability of the algae present in the environment to recover after each episode of inundation. Inundation by freshwater may lead to osmotic stress, disturbance in ion balance, and disturbance in photosynthesis processes. Research on the influence of permanent and pulsing saline incursion on tidal freshwater marshes indicates that disturbance regime is a critical factor for responses of

biological communities and emphasizes the importance of distinguishing between permanent and periodic influences on environment (Li et al., 2022).

Furthermore, microalgae composition is affected by the relationships between salinity, nutrients, sediments, and tide conditions. This is important to mention because the freshwater flooding must not be considered as an isolated disturbance. The ecological impacts of this stress factor develop via interactions of physical, chemical, biological, and hydrological processes. Different disturbances may affect the development over time and resilience of intertidal benthic communities (Cimon & Cusson, 2018).

Despite the existence of various studies that have investigated salinity tolerances and adaptations and microphytobenthic distribution patterns, the ecological impacts of repetitive freshwater flooding events necessitate the need for an integrated concept to interpret them. More specifically, the difference between transient physiological adaptation and structural community reorganization is still important to understand microalgal community responses to repetitive hydrological perturbations. This research fills this gap by developing a conceptual framework of the relationship between freshwater flooding events and microalgae physiology and communities.

It is important to mention that the first aim is the development of theoretical knowledge about the impact of the repeated inundations of fresh water on the structure of the ecosystem in intertidal microalgal communities. Another aim is to investigate the potential influence of disturbance frequency and recovery on the stability of the ecosystem.

The rest of the paper is structured as follows. In Section 2, there is a review of the ecological features of the microalgal communities of the intertidal zone and the disturbance mechanisms that are involved. The next section, Section 3 describes the conceptual approach to research methodology and theory. Section 4 considers the suggested ecological response mechanisms and their importance for community organization and function. Section 5 outlines the theoretical and ecological implications, whereas Section 6 provides suggestions for further research. Section 7 concludes the study.

II. Literature Review

Ecological Characteristics of Intertidal Microalgal Communities

Microalgal communities in the intertidal zone represent an essential part of the coastal benthic ecosystem. Usually, such communities consist of diatoms, but cyanobacteria and other photosynthetic organisms may play a role in their formation. Benthic diatoms usually grow on the upper layer of sediments in the form of biofilm. The occurrence of diatoms is determined by the grain size of the substrate, nutrients, porewater, tidal regime, and light.

The microphytobenthos is important for maintaining ecosystem stability by means of carbon fixation through photosynthesis and extracellular polymer formation. The extracellular polymers have an impact on the cohesion of the sediments as well as their interaction with the overlying water. Moreover, the photosynthesis of the microphytobenthos also plays an important role in oxygen and nutrient cycling in coastal sediments. Studies focused on benthic microalgae communities inhabiting marine stromatolites revealed the significance of the environment in structuring these communities (Rishworth et al., 2016).

The ecological structure of these communities is influenced by interactions between environmental factors and species traits. The ability to move, cellular structure, ability to attach, growth rate, and adaptability to environmental changes affect the survival of microalgae species. These functional traits form a base for the study of possible effects of environmental perturbations on community structure.

Freshwater Inundation as a Hydrological Disturbance

The flooding of areas with fresh water is where the process of fresh water inundation takes place. This happens as a result of river runoff or rainfall into areas that experience tides. The effect of the fresh water inundation on the benthic ecosystem is dependent on the amount of fresh water inundation, mixing of fresh water with seawater, and time taken to restore normal salinity levels in the estuaries.

The abrupt change in salinity will affect the osmotic environment around the microalgal cells. For organisms that are used to living in saltwater environments, they may face changes in water balance in their cells and even imbalances in the ions within those cells. However, it should be noted that different microalgae respond differently due to physiological tolerance differences.

Exposure to freshwater also raises issues regarding biological recovery after disturbance. Biological recovery could be through the regrowth of surviving individuals, migration from nearby populations, or recolonization of disturbed sediments by the species. This has been studied in freshwater algal systems after disturbance to patches and can provide an important ecological background to consider other recovery strategies in the intertidal microalgal communities (Downes & Street, 2005). Multiple disturbances due to freshwater exposure may enhance ecological disturbance if subsequent disturbances occur without physiological recovery.

Physiological Acclimation and Osmotic Regulation

Acclimatization is one of the key ways that microalgae adjust to the variations in their environment. Changes in external salinity can influence the osmotic pressure inside the cell, and the organism needs to control the water and solutes within its body. Compatible solutes like some amino acids are important in osmoregulation.

The diatoms present in the intertidal zones may vary in terms of their ability to regulate their internal environment due to varying salinities. This means that the physiological adaptations are species-specific and dependent on the conditions of exposure. The flooding with fresh water could therefore lead to temporary decreases in metabolic rates in sensitive species.

Repetition also brings up concerns regarding cumulative impacts from the disturbance event. Should the freshwater environment remain constant or return rapidly, then the microalgae may undergo continuous osmotic adaptation, which may increase the physiological cost. On the other hand, should there be sufficient time between disturbances to allow recovery, then the organisms will be able to restore cellular balance and maintain their population continuity.

Community Composition and Species-Specific Responses

Environmental fluctuations in salinity levels may affect microalgal community composition via selective survival, growth, reproduction, and recolonization. Microalgae with greater salinity tolerances are likely to retain their numbers under changing hydrological conditions, while microalgae adapted to stable salinity conditions in the ocean will be less able to persist after exposure to fresh water.

Changes in community response do not have to be reflected in decreased abundance of microalgae. Inundation of freshwater can lead to changes in relative abundance, functional composition, and dominance of specific ecological groups. Studies of toxic microalgae in high salinity estuarine systems have demonstrated that certain species exhibit an amazing tolerance towards their environment, and thus it is necessary to consider the environmental tolerance of particular species (Huang et al., 2024).

The functional traits will offer another lens through which one may interpret these changes. Motility, attachment, cell size, growth mode, and stress tolerance might influence each taxon's capacity to respond to disturbance. Functional ecology allows us to evaluate the changes in communities beyond traditional assessments based on species richness.

Microalgal Community Functioning and Environmental Interactions

Microalgal community composition affects the functioning of the ecosystem. Community composition may affect ecosystem functioning through productivity, nutrient assimilation, oxygen production, and sediment stabilization. Irradiance, temperature, nutrient content, sediments, and biology are other factors that affect ecosystem functioning.

Another important ecological function of tidal marshes is the connectivity of the food web from estuarine to coastal ecosystems. Any changes in ecosystem conditions within the marsh can affect food source availability and energy transfer to higher trophic levels, indicating the greater ecological importance of preserving productive coastal ecosystems (Colombano et al., 2021).

In the same way, nutrient enrichment and shifts in predator numbers may affect the functioning of salt marshes. This shows that the reaction of the living beings to disturbances in the environment is not always explainable based on the factors that operate individually (Deegan et al., 2007). From this it is clear that there are certain environmental conditions that have an effect on the ecological impact of freshwater inundations.

In summary, the literature indicates that an integrated approach to interpretation where disturbance in hydrology has a physiological, composition-based, and functional impact on microalgal communities is appropriate. However, the impact of recurrent flooding with fresh water needs further theoretical synthesis.

III. Conceptual Research Methodology

Research Design

This study employs a conceptual approach to research where the design involves a synthesis of the existing ecological literature on intertidal microalgae, freshwater flows, changes in salinity, acclimatization physiology, and the functioning of benthic ecosystems. This study is meant to offer an explanation for the ecological processes that occur as a result of the periodic flow of freshwater.

This conceptual analysis focuses on intertidal microalgae communities as a biological system that reacts to periodic alterations of its physical and chemical environment. Scientific literature on the tolerance to salinity, species distribution, photosynthetic adaptations, and benthic biofilm ecology is a theoretical basis for establishing the links between the environmental perturbation and physiological, community, and ecosystem-level processes.

Development of the Conceptual Framework

The framework consists of four interrelated aspects that include hydrological disturbance traits, physiological adaptations, community reorganization, and ecosystem functioning. In the case of hydrological disturbances, such characteristics as inundation frequency, intensity, duration, and recovery period are considered. Physiological responses are concerned with osmoregulation, cell stress response, and photosynthesis. Community reorganization is defined in terms of species replacement, relative abundance, functional diversity, and colonization.

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Conceptual Variables and their Relationships

The independent variable of interest is freshwater inundation, which has been described using the following four parameters: frequency, duration, intensity, and recovery period. Salinity changes form the basis of the environmental pathway through which the effect of inundation on biological processes is mediated. Physiological adaptation and tolerance are some of the mediating mechanisms, whereas sediment, temperature, light, and nutrients are environmental modifiers.

Ecological impacts include the community composition, species diversity, functional diversity, microalgal biomass, photosynthetic activity, and ecosystem stability. Such ecological impacts are said to be interrelated since fluctuations in the number of certain taxa can affect both the community composition and functioning of the ecosystem.

Table 1: Conceptual Dimensions and Expected Ecological Relationships Associated with Repeated Freshwater Inundation

Conceptual dimension	Key components	Expected ecological relationship
Hydrological disturbance	Frequency, duration, intensity	Determines exposure magnitude and recurrence
Salinity conditions	Salinity reduction and recovery	Regulates osmotic environmental conditions
Physiological response	Osmotic regulation, acclimation	Influences cellular tolerance and persistence
Community organization	Species composition, richness, functional diversity	Determines community restructuring
Ecosystem functioning	Productivity, nutrient cycling, sediment stability	Reflects changes in ecological performance
Environmental modifiers	Light, temperature, nutrients, sediment	Alters the magnitude of biological responses

The dimensions included in the conceptual framework presented in table 1 include those that have been identified to be important for developing the hydrological model. It is important to note that this framework also considers the role played by environmental modifiers.

Theoretical Propositions

Five theoretical propositions are made from the conceptual framework. First is that an increase in the frequency of freshwater inundation can increase disturbance in the ecosystem as recovery periods may be insufficient for physiological adjustments to occur. Second is that salinity tolerance in individual organisms will explain differences in population survival and community structure. Third is that long recovery periods facilitate physiological recovery and recolonization. Fourth is that abiotic factors such as nutrient levels, light, temperature, and sediment characteristics can affect the inundation-community response link. Fifth is that the structure of the microalgal community can affect primary production and nutrient cycling.

These propositions provide a theoretical basis for future experimental testing and ecological monitoring.

IV. Proposed Ecological Response Framework and Discussion

Effects of Repeated Freshwater Inundation on Salinity Regulation

Salinity reduction is the main environmental mechanism by which the intrusion of freshwater impacts the intertidal microalgal community. Typically, marine and estuarine sediments have their pore water salinities periodically altered. The intrusion of freshwater into these environments may lead to even larger salinity reductions than those caused by tides.

The ecological response will depend on the degree and the length of time for which there is a reduction in salinity levels. Reduced salinity for a short period may result in short-term physiological adaptations, while long-term immersion of an area in freshwater may exceed the tolerance of some marine-adapted organisms.

Thus, there will probably exist a nonlinear association between freshwater inundations and the response of the community. It might allow diverse assemblages of organisms of various tolerance properties to persist in the ecosystem, as moderate disturbances can occur in such environments. Greater intensity or frequency of disturbances may cause more powerful environmental selection, which might favor the survival of taxa with the capability to function under low-salinity conditions.

Physiological Responses and Species Adaptation

Physiological regulation is anticipated to be the controlling factor governing the initial response of specific microalgae taxa upon their exposure to freshwater. Some of the regulatory factors include osmotic regulation, compatible solutes regulation, membrane stability, and photosynthetic regulation.

During the repeated flooding by fresh water, tolerant species may keep their metabolic activity relatively stable, while sensitive species may undergo temporary growth inhibition or impaired photosynthesis.

Acclimatization must not be confused with evolutionary adaptations. Acclimatization occurs when there is physiologic adaptation in an organism or population in shorter time frames, while evolutionary adaptations take place through heritable changes in generations. The present theory will focus on acclimatization and selection processes without necessarily resulting in genetic adaptation.

Changes in Community Composition and Functional Diversity

The impact of repeated flooding by freshwater can have an effect on the taxonomic composition of microalgal communities in the intertidal zone. The relative distribution of freshwater, brackish, and marine forms can depend on the frequency of flooding events.

Community reorganization can include decreases in the relative prevalence of sensitive taxa and an increase in the prevalence of organisms that are tolerant of varying salt content. However, the trends observed will not necessarily be applicable in all cases of intertidal zones due to factors such as sediment characteristics, nutrients, temperature, and tidal immersion.

Functional diversity is another way of looking at these trends. In communities with diverse strategies among species, there can be many functional traits that remain, despite shifts in the taxa present. On the other hand, intense environmental pressure may lower functional redundancy, leading to increased susceptibility to future disturbances.

Influence on Primary Productivity and Ecosystem Functioning

Microalgal photosynthesis is one of the key ecological processes that occur in intertidal sediments. Photosynthesis may be affected by the inundation of freshwater because of variations in salinity, light, nutrients, and sediments. Any temporary change in these factors may affect the process of carbon fixation and distribution of photosynthesizers.

The relation between the composition of community and ecosystem functions does not have to be proportional. The decrease in species diversity does not mean that there will be a proportional decrease in productivity because some of the tolerant species would still carry out efficient photosynthesis. Changes in the composition of the community could affect nutrient uptake and EPS formation.

However, changes in primary production levels might affect not only the quantity but also the quality of nutrients present in the food source. Tidal freshwaters have been studied and show that the nutritional quality of food sources has considerable importance in zooplankton and thus should be considered together with primary production (Müller-Solger et al., 2002).

Additionally, benthic microalgae play a role in stabilizing sediments through the formation of biofilms. Changes in biomass and biofilm structure could impact the physical properties of sediments such as cohesion and susceptibility to erosion. Hence, recurring freshwater inundation can have an effect on the physical stability of sediments through biological means, but how large an effect is dependent on the nature of the microalgal community.

Recovery Intervals and Ecological Resilience

Recovery intervals form an essential part of the proposed conceptual framework. After being exposed to fresh water, intertidal microalgal communities need the right environment to recover physiologically, continue growing, and return to their original community structure.

However, when there is enough time during recovery intervals, survivors can resume their normal physiology and help with recolonization. Otherwise, flooding might prevent the process of recovery from taking place and lead to community restructuring. In other words, the impacts of flooding on ecology will likely be determined by disturbance magnitude as well as recovery intervals between floods.

Ecological resilience in this instance means the ability of microalgae assemblages to retain or recover their ecological structure and functioning in response to freshwater perturbation. Resilience can take the form of physiological resistance, succession of species, colonization, and functional redundancy. The processes listed above should be distinguished individually since the composition of a community can change without a substantial alteration in important ecosystem functions.

Proposed Conceptual Model

This suggested model encompasses hydrologic disturbance, salt water disturbance, physiological adaptation, community reorganization, and ecological reactions. The environmental modifiers affect the magnitude of each link, while recovery time defines the possibility of restoration after two successive freshwater disturbances.

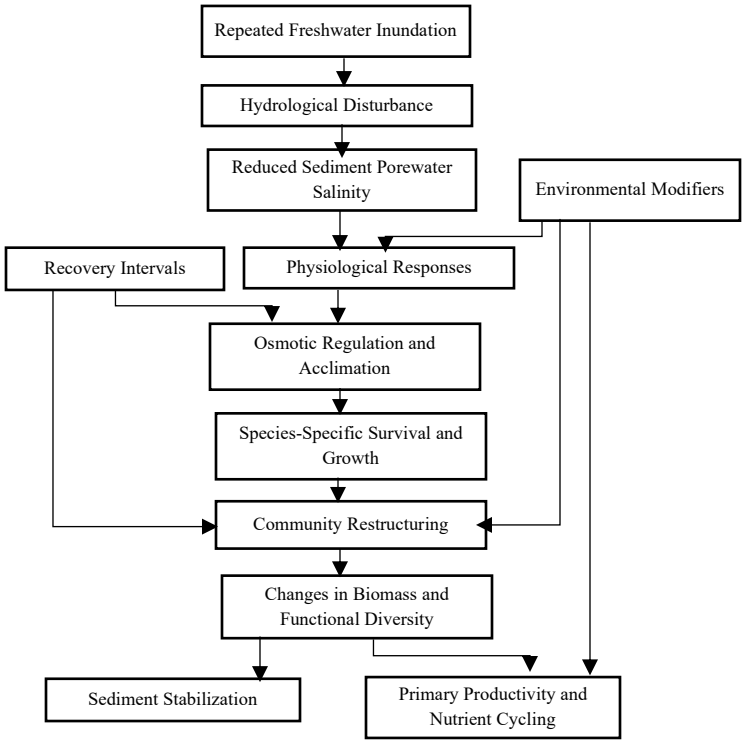


Figure 1: Conceptual Framework Describing Ecological Responses of Intertidal Microalgal Communities To Repeated Freshwater Inundation

The possible interactions between repeated exposure to freshwater and ecological effects are shown in figure 1. The impact of hydrological perturbation on the salinity of the sediment causes a physiological response, which impacts the survival of species and community structuring.

Integrated Ecological Interpretation

Conceptual analysis suggests that freshwater flooding should not only be seen as disturbance, but also as repeated disturbance or disturbance of hydrological nature rather than merely as salinity decrease. The ecological effect of such disturbance is the result of the interaction of several factors.

One such implication is that there will be differences in the taxonomic and functional responses. Community structure can change a lot but not necessarily resulting to a similar reduction in the ecological functions carried out in the ecosystem. Small changes in species abundance can result into great functional changes where the species play important ecological roles. Food web interactions offer another perspective through which the responses can be analyzed (Nielsen, 2001).

The developed framework is consistent with the need for multidimensionality in interpreting the intertidal microalgae's response. It is important that one takes into consideration species diversity, functional diversity, biomass, photosynthesis efficiency, and sediment dynamics when assessing the effects of intermittent freshwater flooding.

V. Theoretical and Ecological Implications

The presented conceptual model is useful in intertidal ecology because it shows the connection between the hydrological regime of disturbances and the physiological responses and effects on communities. The main idea of the model is that the regimes of flooding and recovery should be considered together with the intensity of disturbance when estimating the resistance of microalgae. Besides, the model also broadens the classic views based on salinity by adding functional diversity, physiological acclimation, and ecosystem functioning. From the viewpoint of monitoring, the functional traits of the microalgal community can act as the indicators of the variability in the influx of fresh water into estuaries.

VI. Recommendations for Future Research

The issue requires further research by conducting laboratory and field experiments with cycles of wetting and drying of specimens. Determining the salinity of porewater, biomass of microalgae, composition of microalgae, photosynthesis effectiveness, and extracellular polymeric substances will allow clarifying the mechanisms of restructuring of the community. Molecular and functional approaches might help to identify specific tolerance traits of particular species and changes in functional diversity. The comparison of ecosystems in estuarine environments and coastal areas might help to find out the effects of such factors as the composition of sediments, nutrient supply, tides, and climate.

VII. Conclusion

An example of hydrological disturbance is the occurrence of freshwater flooding, which may cause a physiological, structural, and functional change in microalgal communities in the intertidal zone. The described conceptual model proposes salinity reduction, osmoregulation, species tolerance, community restructuring, and recovery time intervals as essential components of the response process. In addition, it is pointed out that changes in taxonomic composition and function of ecosystems do not have to be correlated linearly. Environmental parameters such as nutrient concentration, light intensity, temperature, and sediment conditions are also important as they can have a significant influence on the response processes. This conceptual review gives the theoretical framework for the evaluation of the adaptability of the microalgae to disturbances in the intertidal ecosystem.

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