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Analysis of Seagrass Growth Characteristics and Environmental Adaptability

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Abstract: *Seagrasses, as globally distributed marine angiosperms, form seagrass beds which are among the most productive ecosystems and provide some of the highest value ecosystem services in the Earth's biosphere. However, with increasingly severe global climate change and frequent human disturbances, the decline of seagrass beds has already impacted the marine environment and biodiversity. This paper systematically reviews the current understanding of seagrass environmental adaptability. It clarifies the basic concept of seagrasses, their geographical distribution characteristics, morphological attributes, and the importance of their ecological functions. It provides a detailed analysis of seagrass adaptation strategies to common environmental stresses, primarily heat stress, and compares these with common terrestrial angiosperms. Subsequently, it elaborates on the current survival status of seagrasses and the main reasons for seagrass bed decline. Finally, based on the aforementioned research conclusions, it summarizes the core pattern of seagrass adaptation mechanisms. This paper aims to provide a theoretical reference for deepening research and conservation practices in seagrass-related fields, particularly for understanding how seagrasses utilize their own adaptation mechanisms to cope with environmental stresses induced by climate change and human disturbances.*

Keywords: *Seagrass Growth; Characteristics; Environmental Adaptability*

1. Introduction

Seagrass is a type of monocotyledonous plant that grows in coastal marine areas, and it is an important component of marine ecosystems such as seagrass beds. There are over seventy seagrass species globally, most of which are distributed in tropical regions, with a few species living in temperate waters. Coastal marine ecosystems, such as salt marshes, mangroves, and seagrass beds, can absorb 16.5 million tons of carbon dioxide annually, yet seagrass beds alone account for 15% of the total carbon sequestered in global waters. As one of the most productive and biodiverse coastal marine ecosystems, seagrass beds play a crucial ecological role in the coastal marine environment: they stabilize the marine environment, support marine biodiversity, and provide many important ecosystem services for humans. Given the important ecological significance of seagrass beds and their role as carbon sinks, they are considered a natural means to control the rate of global climate change and have received increasing attention in recent years. However, global climate change itself also impacts seagrass survival and seagrass bed ecology; for instance, rising water temperatures lead to decreased seagrass productivity or even large-scale mortality, causing a contraction and northward shift in the global distribution of seagrasses. Notably, as a sessile plant group, individual seagrasses cannot avoid unfavorable environments through migration. Therefore, during long-term evolution, they have developed systematic environmental stress response mechanisms, covering gene expression regulation at the molecular level, metabolic pathway adjustments, and adaptive modifications in morphological structure. In-depth analysis of these response mechanisms is not only key to revealing seagrass adaptation strategies but also serves as the core basis for scientifically predicting the dynamic trends of seagrass beds under future climate change and formulating targeted conservation and restoration strategies. Based on this, this paper systematically reviews the environmental adaptation mechanisms of seagrasses, aiming to provide references for seagrass conservation practices and related research.

2. Morphological Characteristics and Warming Adaptability of Seagrasses

2.1 Species and Distribution Characteristics of Seagrasses

Seagrasses are currently the only discovered group of angiosperms fully adapted to marine life, although there are some transitional species, such as *Ruppia*, that live in brackish water areas like estuaries. Seagrass is not a single species but a group of marine plants that evolved convergently from different freshwater ancestors through multiple transitions to the marine environment. As angiosperms, seagrasses have differentiated roots, stems, and leaves, and reproduce through flowers and fruits developed from closed ovaries. Additionally, seagrasses have significant submerged plant characteristics: such as well-developed root systems and rhizomes, reduced mechanical tissues like vascular bundles, leaves without stomata, and underdeveloped cuticles.

The ecosystem formed by patches of growing seagrasses is called a seagrass bed. Together with coral reefs and mangroves, they are known as the three typical coastal marine ecosystems. Strictly speaking, "seagrass bed" generally refers to a seagrass ecosystem dominated by one or multiple seagrass species, emphasizing its systemic integrity and function; whereas "seagrass meadow" refers to a community where seagrasses are the dominant species, focusing on the seagrass patches and their distribution. [1] Seagrass bed ecosystems possess various ecological functions and also provide immense ecosystem services to humans.

2.2 Growth Environment

Seagrasses are distributed almost globally. The six floristic regions proposed based on distribution of species and the influence of the tropical and the temperate zones (Temperate North Atlantic, Temperate North Pacific, Mediterranean, and Temperate Southern Ocean regions; Tropical Atlantic and Tropical Indo-Pacific regions) are more widely accepted in seagrass research.

Based on the temperature of their living environment, seagrasses can be divided into temperate seagrasses and tropical or subtropical seagrasses. The former, including genera like *Zostera* and *Phyllospadix*, have an optimal growth temperature range of 11.5°C–26°C; the latter, including genera like *Enhalus*, *Halodule*, and *Halophila*, have an optimal growth temperature range of 23°C–32°C. [2] Seagrasses mainly grow in sandy or muddy substrates in the intertidal and subtidal zones. Due to water absorption of specific wavelengths and the light requirements of seagrasses, light is the primary factor determining the distribution of submerged plants, causing most seagrasses to be distributed in coastal waters within 20 meters depth, with a maximum distribution depth of only 90 meters. Besides, suitable salinity, water flow, nutrient concentration, acidity, etc., are all factors promoting the healthy growth of seagrasses.

2.3 Seagrasses and Environmental Stress

Seagrasses have evolved defense mechanisms to cope with various stresses. These mechanisms significantly reduce the susceptibility of seagrasses to common stresses (such as heat stress, light stress, salt stress, etc.), enabling them to survive and reproduce in non-ideal, fluctuating environments, and also providing possibility for adapting to climate change and expanding their distribution range. The defense mechanisms of seagrasses under extreme environments allow for a deeper understanding of their survival and adaptation under global climate change, thus providing scientists with more ideas for seagrass conservation. Therefore, seagrasses have research value in areas such as oxidative stress, high-temperature adaptation, and light adaptation.

3. High-Temperature Adaptability

Heat stress typically refers to environmental temperatures 10-15°C above the plant's optimal growth temperature. Its essential impact on seagrasses lies in the changes in molecular structures and abnormalities in biochemical reactions under conditions of excess environmental energy. At the microscopic level, high temperatures cause conformational changes in proteins, inactivation of some enzymes, increased fluidity of lipid membranes, and also affect the electron transport chains of photosynthesis and respiration, leading to massive generation of ROS (Reactive Oxygen Species), causing the plant to simultaneously suffer from oxidative stress. These microscopic changes manifest macroscopically as decreased photosynthetic productivity, slowed growth, changes in morphological structure, and even large-scale mortality of seagrasses.

3.1 Core Molecular Mechanisms of Seagrass Heat Adaptation

The adaptation mechanism most associated with high temperature in plants, the Heat Shock Response (HSR), refers to the upregulation of Heat Shock Protein (HSP) expression when plants suffer heat stress. As molecular chaperones, these different types of heat shock proteins can bind to proteins and some lipids, stabilize their structures at high temperatures, promote correct protein folding or degradation, and maintain cellular homeostasis. Heat shock proteins are divided into several types, namely small heat shock proteins (sHSPs), HSP60, HSP70, HSP90, HSP100, etc., which play different roles at different time points after the plant is subjected to heat stress, cooperating to reduce denatured protein molecules and their impact on the cells from various aspects.

Among them, small heat shock proteins (sHSPs) are the first heat shock proteins to respond to heat stress. They bind their own hydrophobic parts to the exposed hydrophobic ends of denatured proteins, preventing proteins from combining with each other to form precipitates. This process usually does not consume ATP. Some small heat shock proteins can also bind to the phospholipid bilayer, stabilizing the cell membrane structure. Studies have shown that the small heat shock protein AtHSP21 accumulates rapidly after heat stress and possesses a "heat memory" function.[3] Thus, it can be inferred that some small heat shock proteins likely play an important role in plant heat acclimation. Although the unique secondary return to the marine environment during seagrass evolution has led to differences in HSR, including difference in transcriptional regulation, compared to terrestrial angiosperms , the function of heat shock proteins and the response of HSR-related genes in seagrasses are fundamentally similar to those in terrestrial angiosperms. Therefore, for seagrasses as well, HSPs maintain the basic homeostasis and life activities of various important proteins (such as the D1 and D2 proteins of photosystems), conferring adaptability to the currently rising water temperatures.

3.2 Antioxidant System Alleviates Heat Stress

Since high temperatures also cause plants to endure oxidative pressure, the antioxidant system plays a non-negligible role when seagrasses resist heat stress. Specifically, high temperatures increase the oxygen consumption of seagrasses and can even directly disrupt the electron transport chains of photosynthesis and respiration, generating large amounts of reactive oxygen species. Furthermore, high temperatures reduce the activity of antioxidant enzymes, leading to ROS accumulation. At this point, the aforementioned antioxidant system is activated. Seagrasses such as *Z. marina*, *P. oceanica*, *C. nodosa*, and *T. hemprichii* all cope with oxidative stress caused by high temperatures through this method. However, the types of antioxidant enzymes involved in the response, the degree, and speed of the response are influenced by many factors such as seagrass species, habitat, and stress intensity and duration. Similar to HSR, for temperate seagrasses and ecotypes less adaptive to high temperature environments, the antioxidant system responds more slowly under stress and recovers more slowly. But unlike HSR, which has more component participating in heat-adaptive species, temperate species have more antioxidant components participate in the antioxidant response[4], likely due to their higher susceptibility to heat stress itself, causing them to generate more ROS and endure more severe oxidative stress compared to tropical seagrasses.

4. Adaptability to High-Light Stress and Salt Stress

4.1 Light Stress

Light is the source of energy for plant physiological activities and growth; it determines the ecological thresholds of seagrasses and is the primary limiting factor for seagrass photosynthetic productivity and seagrass bed distribution. Since both high and low light are common non-ideal conditions during the seagrass life cycle, seagrasses have evolved self-protection mechanisms against high light and ways to maintain productivity under low light.

For high-light stress, the main defense mechanism in seagrasses is non-photochemical quenching. Specifically, under high light, seagrasses upregulate the expression of genes related to the xanthophyll cycle and produce more xanthophyll, a core chemical for non-photochemical quenching (qE). Generally, High-light stress also leads to massive generation of reactive oxygen species in seagrasses, which is related to damage to the photosystems. In this case, the antioxidant system is activated to

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eliminate ROS and minimize secondary damage caused by ROS. However, for some species adapted to high light (such as *Halophila ovalis*), the amount of ROS generated under such conditions shows no significant change[5], likely due to higher levels of xanthophyll-related gene expression and a well-prepared, faster non-photochemical quenching response.

For low-light stress, seagrasses alter the ratio of chlorophyll a to chlorophyll b, change chloroplast density, and adjust the light compensation point and light saturation point to maintain the minimum photosynthesis level necessary for survival.

4.2 Salt Stress

As the only group of angiosperms adapted to marine life, seagrasses endure more frequent and severe salt stress compared to other plants, and have accordingly evolved more powerful salt stress adaptation mechanisms. Salinity, i.e., ion concentration, affects physiological activities such as photosynthesis by influencing osmotic pressure and protein activity, so salt stress weakens the plant's antioxidant capacity, and disrupts intracellular homeostasis.

For seagrasses, an important substance for osmoregulation is proline. Seagrasses accumulate large amounts of proline within cells to ensure osmoregulatory capacity. When external salinity increases, placing seagrasses in a hyperosmotic state, they can increase the cytoplasmic proline concentration, reducing intracellular water loss without affecting the intracellular ion concentration, thus avoiding ion toxicity. Liu Mingzhong et al., in their study on *Thalassia hemprichii* and *Cymodocea rotundata*, mentioned that the proline content of both seagrasses increased under salinity fluctuations. The proline content of Thalassia hemprichii began to increase significantly under moderate salinity fluctuations, while Cymodocea rotundata was more sensitive, starting to increase under mild fluctuations[6]. Salt stress can also cause cell membrane lipid peroxidation by increasing plant cell membrane permeability and affect the activity of antioxidant enzymes like CAT. Therefore, the antioxidant system also participates in salt stress recovery, maintaining oxidative balance to a limited extent by increasing expression levels and enhancing the activity of some enzymes.

4.3 Oxidative Stress and the Antioxidant System - A Defense Mechanism for Multiple Stresses

As repeatedly mentioned previously, when seagrasses face various environmental stresses, such as heat stress, high-light stress, salt stress, and mechanical stress, an increase in reactive oxygen species levels commonly occurs. The reasons usually lie in the obstruction of photosynthesis or respiration and reduced activity of antioxidant enzymes. Reactive oxygen species are a class of highly reactive oxygen-containing molecules and are major stress signaling molecules. However, at high concentrations, they can damage cellular DNA, lipids, and proteins, causing oxidative stress. Therefore, oxidative stress can be seen as a derivative stress, and the antioxidant system becomes an important part of the response and recovery from multiple common stresses. Different antioxidant enzymes, non-enzymatic antioxidants, and antioxidant cycles cooperate with each other, forming a complex and precise antioxidant system that enables seagrasses to cope with frequently occurring oxidative stress and recover more quickly from various stresses.

5. Decline of Seagrass Ecosystems

5.1 Natural Disasters and Interspecific Competition

Natural disasters and interspecific competition are two major causes of seagrass ecosystem decline, both belonging to natural factors. Natural disasters, such as typhoons, rainstorms, storm surges, and extreme high temperatures, can cause devastating damage to large areas of seagrass beds. Specifically, regional extreme high temperatures impose extreme heat stress and desiccation stress on seagrasses in a short time, especially for intertidal seagrasses. These seagrasses are exposed to air at certain times, and high temperatures can cause severe scorching or even death. These extreme weather events are highly destructive to seagrass beds, and the unpredictability and uncontrollability of natural disasters make them difficult to avoid.

Regarding interspecific competition, the main interspecific competition faced by seagrasses is with algal plants and with the invasive species *Spartina alterniflora* in Chinese seagrassbed. Increased nutrient content in seawater stimulates the rapid growth and reproduction of algae. These algae not only consume large amounts of dissolved inorganic carbon and nutrients in the water, but some species also

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attach to the surface of seagrasses, affecting their photosynthesis, material exchange, and the leaf surface microenvironment.

Besides natural disasters and invasive species that cause massive damage in the short term, chronic climate change is gradually altering the distribution of seagrasses. Excess carbon dioxide in the atmosphere is the chief culprit of global warming. Global warming leads to an overall increase in ocean water temperature. The resulting heat stress not only affects the survival and productivity of seagrasses but also causes a macroscopic northward shift in their overall distribution. Consequent changes in ocean salinity and sea-level rise expose seagrasses to salt stress and low-light stress, respectively. Gradually rising carbon dioxide concentrations also alter ocean acidity. Some studies indicate that this provides sufficient inorganic carbon, giving seagrasses a competitive advantage[7], but the negative impacts brought by climate change have far exceeded the advantages gained from increased CO_2 levels.

It is worth mentioning that climate-related research has found that global climate change is also related to the intensity and frequency of natural disasters. Nowadays, although such global climate change posing challenges to seagrasses is accelerating, this relatively chronic environmental change itself might be the disturbance that seagrasses are most likely to cope with through stress resistance mechanisms and adaptive evolution.

5.2 Human Disturbances

Many human activities cause anthropogenic disturbances, such as land reclamation, maritime traffic construction, fisheries activities, and land-based pollution. Land reclamation involves using sediment to fill large areas of seabed to create land for expanding agricultural or urban construction land. During land reclamation, if there is a lack of awareness regarding the protection of seagrass ecosystems, it will inevitably lead to the entire burial of seagrass beds.

The main impact of fisheries activities is seabed destruction. High-intensity digging in the intertidal zone, shellfish collection via boat sand suction, and collecting peanut worms using high-pressure water jets disrupt the seabed environment and also cause water turbidity, severely affecting the various organisms in the seagrass bed ecosystem. Pollution is also a great part of human disturbance. Land-based pollution and pollution caused by mariculture are two main sources of pollution. Pollutants contained brought by the sources lead to localized increases in bacterial concentration, heavy metal exceedances, eutrophication, and increased water turbidity, harming seagrasses in multiple ways.

Human activities are among the few factors that can be fully controlled in seagrass bed conservation. Given the enormous ecological value created by seagrass beds, people should balance environmental protection and economic development, or minimize damage to the seagrass ecosystem and even the entire marine environment through methodological innovation.

6. Conclusion

The article summarizes the morphological and molecular responses of seagrasses to oxidative stress, heat stress, light stress, and salt stress, and analyzes the mechanisms by which seagrasses resist stress. It also analyzes the reasons for seagrass bed decline and the involved stresses, defining which factors among these we can intervene in, which seagrasses are expected to adapt to, and which are uncontrollable. Under the evolutionary process of returning to the sea and its selective pressures, seagrasses have acquired resistance and adaptability to various environmental stresses, including stress perception, signal transduction, an antioxidant system used for recovery after multiple stresses, stress-specific gene expression and its related metabolic pathways, etc. These stress adaptation mechanisms are conserved among plants, especially among angiosperms. That is, on the basis of common plant characteristics, seagrasses, through genetic mutations (including gene loss, whole-genome duplication, etc.) and natural selection, have fine-tuned some details of these stress resistance systems, such as the expression level of certain proteins and the differentiation of regulatory elements, forming the current seagrass stress resistance mechanism that shares the same "program logic" but has different "parameters" compared to terrestrial angiosperms. From these subtle differences in regulatory levels, we can glimpse how to develop personalized conservation measures for different species of seagrasses and other aquatic plants, and even understand how to modify the genes or phenotypes of species to enable them to adapt to this environment constantly affected by humans. Therefore, when studying the stress resistance and adaptability of seagrasses, reference can be made to the stress resistance mechanisms of terrestrial angiosperms. The patterns summarized

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therefrom can not only be widely applied to further research on seagrasses and the formulation of conservation strategies but can also be compared in parallel with the evolutionary pathways of other plants or in reverse contrast with the evolutionary process of plant terrestrialization, gaining a deeper understanding of plant evolution.

Although seagrasses have evolved relatively comprehensive multiple stress resistance mechanisms, seagrass beds today still face severe global decline under human disturbances and climate-related disasters. The current growth status of seagrasses deserves attention, and the protection of seagrass beds is urgent. Future research can evaluate the adaptability of different seagrass species under current human disturbances and climate change from multiple aspects, propose potential evolutionary strategies, and assess the priority of conservation for different species. Furthermore, the impacts of different environmental stresses on seagrasses are not independent chains but an interconnected network, as even the pathways perceiving different stresses within seagrasses are largely shared. Since most past research has focused on single stresses, future studies could emphasize the interaction of multiple stresses, constructing a "network" of multi-stress adaptation. Nowadays, attention to seagrass beds is gradually increasing. Even though deficiencies and gaps remain, we should believe that this field will eventually develop and we can finally win this battle in marine biodiversity conservation.

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