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Commentary

Molecular and ecological dimensions of stress tolerance in plants under global environmental change

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Global environmental change, encompassing climate warming, altered precipitation patterns and increased frequency of extreme events, poses unprecedented challenges to plant survival, growth and productivity. Stress tolerance in plants involves a complex interplay between molecular mechanisms, physiological responses and ecological interactions. At the molecular level, plants employ strategies including stress-responsive gene expression, signal transduction pathways, antioxidant systems and epigenetic regulation to withstand abiotic stressors such as drought, salinity and heat. Ecologically, plant stress tolerance is mediated by interactions with soil microbiomes, mycorrhizal networks and neighboring vegetation, which collectively modulate resource acquisition, nutrient cycling and resilience to environmental perturbations. This article synthesizes current knowledge on the molecular and ecological dimensions of plant stress tolerance, highlighting integrative approaches to enhance resilience in natural and managed ecosystems. Understanding these mechanisms is critical for predicting vegetation responses to global change and informing conservation, restoration and agricultural strategies.

Keywords: Plant stress tolerance, Molecular mechanisms, Abiotic stress, Soil microbiome, Mycorrhizal networks, Climate change, Ecological resilience, Drought adaptation, Heat stress, Salinity.

Introduction

Agricultural systems worldwide are under pressure to meet rising food demands while minimizing environmental degradation. Intensified agricultural practices—monocultures, high fertilizer and pesticide use and irrigation—have dramatically increased food production. However, these practices often degrade soil structure, reduce biodiversity, pollute water resources and disrupt regulating ecosystem services. In contrast, ecological restoration, including reforestation, wetland rehabilitation and riparian buffer establishment, aims to recover ecosystem functionality, enhance carbon sequestration and improve biodiversity, but may limit short-term crop yields. Ecosystem services—provisioning, regulating, supporting and cultural—are often in competition and land-use decisions create trade-offs between these services. Understanding these trade-offs is critical for developing sustainable land management strategies that balance agricultural production with ecological integrity. This article synthesizes research on ecosystem service trade-offs under agricultural intensification and restoration, highlighting mechanisms, spatial and temporal scales and strategies for sustainable multifunctional landscapes (Lesbarreres D, et al. 2012). Agricultural intensification enhances provisioning services, primarily food, fiber and bioenergy production. Monocultures, mechanization and chemical inputs increase yields per unit area, supporting local and global food security. Crop selection and irrigation improve resilience to climate variability, while fertilizers and pesticides enhance short-term productivity. Intensification, however, often comes at the expense of other ecosystem services, creating a complex balance between production and ecological integrity.

Description

Plants are the foundation of terrestrial ecosystems, driving energy flow, carbon sequestration and ecosystem services. However, global environmental change—including rising temperatures, altered precipitation regimes, soil degradation and anthropogenic pollution—threatens plant productivity and ecosystem stability. Abiotic stressors such as drought, heat, salinity and flooding induce physiological and molecular disruptions, including Reactive Oxygen Species (ROS) accumulation, membrane damage and impaired photosynthesis. Understanding how plants tolerate these stresses requires integrating molecular insights with ecological perspectives (Torres A, et al. 2016). Stress tolerance in plants is not solely determined by individual physiological responses but is also influenced by interactions with soil microbiota, mycorrhizal networks, neighboring plant communities and landscape context. Soil microorganisms can enhance nutrient uptake, modulate hormone signaling and improve plant resilience under drought and salinity. Similarly, mycorrhizal symbioses facilitate water and nutrient acquisition, contributing to plant fitness under environmental stress. These molecular and ecological dimensions of stress tolerance collectively shape plant performance, survival and ecosystem functioning under global change scenarios.

Plants sense environmental stress through receptors located in cell membranes and organelles. Abiotic stress triggers signal transduction pathways involving calcium ions, Reactive Oxygen Species (ROS), Mitogen-Activated Protein kinases (MAPKs) and phytohormones such as Abscisic Acid (ABA), ethylene and salicylic acid. These signaling cascades regulate the transcription of stress-responsive genes, including those coding for osmoprotectants, heat-shock proteins, aquaporins and antioxidant enzymes. Stress-tolerant plants often exhibit upregulation of genes involved in protective and adaptive processes (Fashola MO, et al. 2016). Heat-Shock Proteins (HSPs) stabilize protein structures during thermal stress, while Late Embryogenesis Abundant (LEA) proteins protect cells during drought or salinity. Osmoprotectants such as proline, glycine betaine and trehalose maintain cellular osmotic balance. Transcription factors, including DREB, MYB and NAC families, orchestrate the expression of these stress-related genes, allowing rapid and coordinated responses. Abiotic stress commonly results in overproduction of ROS, leading to oxidative damage to DNA, proteins and lipids (Maestri E, et al. 2002). Plants counteract this through enzymatic antioxidants (superoxide dismutase, catalase, peroxidases) and non-enzymatic compounds (ascorbate, glutathione, carotenoids). Maintaining redox homeostasis is critical for cellular survival and the modulation of stress signaling pathways.

Recent studies reveal that stress tolerance can be mediated by epigenetic modifications, including DNA methylation, histone acetylation and non-coding RNAs. These modifications influence gene expression without altering the DNA sequence and can prime plants for faster or stronger responses to recurring stress-a phenomenon termed stress memory. Epigenetic regulation allows plants to "remember" prior stress events, enhancing resilience under fluctuating environmental conditions. The rhizosphere harbors diverse microbial communities, including bacteria, fungi and archaea, that influence plant stress tolerance. Beneficial microbes can induce systemic resistance, enhance nutrient acquisition and modulate hormone signaling. For instance, drought-adapted bacterial communities improve root water uptake, while certain Pseudomonas and Burkholderia strains enhance salinity tolerance by producing osmolytes and phytohormones (Simha P, et al. 2017). Ectomycorrhizal and arbuscular mycorrhizal fungi form symbiotic networks connecting plant roots to soil nutrient pools. These networks improve water and nutrient access, particularly under drought and nutrient-limited conditions and facilitate carbon allocation and signaling among plants. Mycorrhizal associations also contribute to soil aggregation, reducing erosion and enhancing ecosystem stability under climatic stress.

Conclusion

Plant stress tolerance under global environmental change is governed by a complex interplay of molecular mechanisms and ecological interactions. At the molecular level, stress perception, gene regulation, antioxidant defense and epigenetic memory enable plants to withstand abiotic challenges. Ecologically, soil microbiomes, mycorrhizal networks, plant–plant interactions and landscape-level processes modulate resilience and ecosystem functioning. Integrating these molecular and ecological perspectives provides a comprehensive framework for understanding plant adaptation and resilience under climate stress. Such knowledge is vital for sustainable agriculture, biodiversity conservation and ecosystem management.

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Conflict of Interest

The authors declare no conflict of interest.

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