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Vegetation Patterns: Structures and Dynamics

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Abstract. Vegetation patterns are a hallmark of ecosystem self-organization, emerging from the intrinsic dynamics of nonlinear feedback mechanisms and spatiotemporal interactions. This review systematically explores and examines the structural characteristics of these patterns, the phenomena of multistability, and their implications for ecosystem stability through the lens of mathematical modeling and dynamical systems theory. In particular, reaction-diffusion models serve as a key analytical tool, revealing how local positive feedback and non-local negative feedback drive self-organized spatial structures via Turing bifurcation. Bifurcation theory and potential landscape analysis further elucidate ecosystem multistability, quantifying critical transitions among uniform vegetation, patterned states, and bare soil under environmental conditions. Advances in spatial metrics, including traditional statistical measures (e.g. variance, autocorrelation) and emerging complexity-based indicators (e.g. hyperuniformity, spatial permutation entropy) provide robust methods for detecting ecological functional shifts and early-warning signs of regime shifts. Additionally, restoration strategies grounded in structural optimization, such as optimal control theory, offer a theoretical framework for vegetation pattern reconstruction and stability regulation, particularly in arid and semi-arid regions. Future research should integrate multiscale modeling and interdisciplinary approaches to deepen our understanding of vegetation structure-function relationships. Such efforts will yield both theoretical insights and practical solutions for mitigating global ecological degradation and climate change.

AMS subject classifications: 35K57, 35B36, 92C80

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1 Introduction

Vegetation patterns are a critical characteristic of ecosystems, serving as the "fingerprints" of ecosystems, containing rich ecological information. These patterns reflect the spatial distribution of vegetation, including uniform, patchy, and striped distribution, which result from complex interactions between biotic and abiotic factors [55,93,114,118]. In arid and semi-arid regions, vegetation commonly forms patchy distributions separated by bare soil or sparsely vegetated areas, reflecting both the scarcity of water resources and adaptive strategies for resource competition. Analyzing vegetation patterns enables the assessment of resource allocation and provides insights into ecosystem health and stability. In addition to serving as indicators of ecosystem states, vegetation patterns play a fundamental role in ecosystem functioning [25, 66, 75, 82, 101, 132]. Different spatial patterns significantly influence nutrient cycling, energy flows, and biodiversity maintenance. Patterns with high connectivity facilitate species migration and dispersal, contributing to population stability. Moreover, well-organized patterns improve resource use efficiency, enhance resilience to disturbances, and strengthen recovery potential. Consequently, the study of vegetation patterns is essential for understanding ecosystem mechanisms, predicting ecological changes, and developing effective strategies for ecological management.

In recent years, significant progress have been made in understanding the mechanisms underlying vegetation pattern formation and advancing theoretical models [13, 34, 76, 86, 102, 104, 119, 131]. Classical nonlinear dynamic models, such as the Klausmeier [55], Rietkerk [41, 84], and Gilad models [35, 36], have been the foundational tools for elucidating the formation and evolution of vegetation patterns. These models describe how positive and negative feedback mechanisms drive pattern formation through the interplay of water dynamics: positive feedback promotes vegetation growth by locally accumulating water, while negative feedback constrains overexpansion via resource competition. In arid and semi-arid regions, these mechanisms lead to the emergence of patchy or striped vegetation patterns, highlighting the critical role of water as a limiting resource. With the advancement of research, these foundational models have been extended to accommodate more complex ecosystem dynamics. For example, introducing time-delay effects can capture the lag in vegetation responses to environmental changes, which is crucial for studying ecosystem dynamics under climate change and human disturbances [46, 109, 123]. Additionally, the influence of plant reproductive strategies (e.g. seed dispersal distances and mechanisms) has been integrated into modeling frameworks [1, 7, 27, 28, 81, 120]. Furthermore, the integration of competitive behaviors among plants, such as root distribution competition for water and nutrients, further refine models to better represent resource allocation and competition processes [59, 69, 80]. Notably, recent research have increasingly focused on coupling vegetation models with climate systems to explore bidirectional effect between vegetation and climate [19, 20, 54, 78, 103]. For instance, changes in precipitation patterns not only influence vegetation distribution but also modify regional climates via evapotran-