学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Algal Blooms as Marine Ecosystem Risk: Forecasting Spread and Biogeochemical Stress
（海洋生態系リスクとしての藻類の爆発的増殖: 拡散と生物地球化学的ストレスの予測）

Algal blooms represent a complex ecological challenge, causing significant impacts to aquatic ecosystems and human well-being. Traditional methods for understanding and predicting algal blooms often struggle to capture the intricate interplay of variables and environmental factors driving these events. Consequently, it is necessary to uncover innovative approaches that can overcome these limitations. This dissertation aims to bridge this gap by integrating causal network inference and graph neural networks. A novel causal inference model is introduced, utilizing 'transfer entropy difference' to quantify one-directional information flow among variable pairs, effectively modeling algal blooms' dynamics. This approach is further enriched by combining one-directional transfer entropy differences with graph neural networks, facilitating time-series predictions for algal blooms. The significance of this work lies in its capacity to analyze the causal inference network's information dynamics, structure, and functional features. This analysis enables the identification of algal blooms' spatial dynamic responses to environmental changes, even without spatial dependencies. The incorporation of macroecological analyses enhances the comprehension of how algal blooms react to shifts in environmental factors and geographic alterations. Moreover, the integration of causal relationships (transfer entropy differences) into the construction of graph neural networks is also innovative. This design enhances variable connections and mitigates information redundancy from high-dimensional data. By utilizing prior causal knowledge derived from 'transfer entropy difference', the model eliminates the need to independently identify pivotal variables, thus enhancing forecasting accuracy. This study provides insights into complex ecosystem problems, contributes to the proposition of targeted preventive approaches and measures, and achieves effective prediction and inference of complex systems with multiple factors.

Chapter 1 discusses the signs that denote changes occurring within ecosystems, particularly in marine environments. The chapter highlights the value of studying harmful algal blooms as a microcosm reflecting alterations in marine ecosystem dynamics. Furthermore, the complexity of ecosystems is emphasized, underscoring the necessity of considering multifactorial relationships when assessing the potential risks of ecosystems.

Chapter 2 of the dissertation explores causal inference and causality-based neural network models for predicting algal blooms, focusing on the CHLa indicator. The causal inference model identified influential observation stations and their interrelationships during the CHLa observation period. The study investigated triggers and risk indicators for abrupt and prolonged blooms at specific influential stations. Additionally, the causality-based graph neural network effectively predicted CHLa's geographic

distribution without relying on spatial correlations.

Chapter 3 applies causal inference modeling to the 2005 harmful algal bloom in Florida Bay. The model's accuracy is validated by comparing its inferring results with the actual event's spatial progression. The study quantifies the bloom's effects on water quality at different stations and suggests control strategies. It also evaluates ecosystem stability before and after the event, highlighting the ecosystem's self-regulation capacity.

Chapter 4 offers a comprehensive evaluation of the proposed causal inference method and causality-based graph neural networks. The study analyzes CHL-a dynamics, other environmental factors, and ecosystem risks. A predictive biogeochemical network is created to understand algal blooms and associated risks. The findings include improved prediction accuracy for flash blooms using transfer entropy and identifying critical CHL-a thresholds for outbreaks. The study highlights ecosystem vulnerability and the potential for ecological collapse due to biogeochemical disruption. Shifts in bloom patterns also underscore environmental impacts. Overall, this chapter advances understanding of algal blooms dynamics, ecological shifts, and systemic risks in changing environments.

Chapter 5 summarizes all the previous chapters and highlights the widely used of the causal inference and causality-based graph neural networks that we proposed. Beyond the scope of the present study, these concepts stand adept at extrapolating and anticipating system behaviors and information dynamics across a spectrum of intricate scenarios, extending to domains like medicine, social networks, and brain sciences, where conventional methodologies may falter.