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# Sea Urchin Population Dynamics in Seagrass Ecosystem: A Model to Mitigate Baren Seagrass Ecosystem

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## ABSTRACT

The relationship between sea urchins and seagrass ecosystems is fundamental to maintaining coastal ecological balance. Sea urchins, as primary herbivores in seagrass meadows, play a crucial role in regulating algal growth, which supports overall ecosystem health. However, when sea urchin populations exceed certain thresholds, their herbivory can shift from a beneficial process to one that undermines the integrity of seagrass beds. This study employs mathematical modeling to explore the population dynamics between sea urchins and seagrass, with a particular focus on overgrazing and the formation of barren ecosystems. The research highlights a significant gap in current ecological understanding—the inability to pinpoint the critical tipping point at which sea urchin populations become unsustainable for seagrass survival. By simulating the interaction between these species, this study provides valuable insights into coastal management strategies aimed at preserving healthy seagrass ecosystems. The findings could help inform policies to maintain balanced herbivory and to prevent the collapse of seagrass meadows into barren zones, ensuring long-term ecological stability.

## INTRODUCTION

Seagrass ecosystems represent one of nature's most remarkable achievements in marine ecology, serving as the foundation for diverse and productive coastal environments. These underwater meadows fulfill crucial ecological functions: they sequester carbon at rates surpassing terrestrial forests, protect coastlines from erosion, and provide essential habitats for countless marine species **(McKenzie & Yoshida, 2020; Krumhansl *et al.*, 2021)**. Yet, these vital ecosystems exist in a delicate balance, particularly when it comes to their relationship with herbivores like sea urchins.

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The interaction between seagrass and sea urchins exemplifies the complex dynamics of marine producer-consumer relationships **(Sulistiawan *et al*., 2019)**. Sea urchins, through their grazing behavior, traditionally help maintain ecosystem health by controlling algal growth that might otherwise overwhelm seagrass beds. However, when their populations exceed certain thresholds, these same herbivores can transform from ecosystem regulators into agents of destruction, potentially converting vibrant seagrass meadows into barren underwater deserts **(Rifai *et al*., 2023)**.

Recent research has highlighted the accelerating decline of seagrass ecosystems worldwide, driven by a combination of factors including coastal development, pollution, and climate change **(Krumhansl *et al*., 2021; Peralta *et al*., 2021)**. While these broader environmental pressures have received considerable attention, the specific role of sea urchin herbivory in seagrass decline remains less thoroughly quantified. This knowledge gap is particularly concerning given the observed increases in sea urchin populations across various marine environments, often attributed to the disruption of natural predator populations through overfishing.

The challenge in understanding these dynamics lies in their inherent complexity. Seagrass growth patterns respond to multiple environmental variables, while sea urchin population dynamics fluctuate based on food availability, predation pressure, and environmental conditions **(Nadiarti *et al*., 2021)**. Traditional ecological studies have often focused separately on either seagrass ecology or sea urchin biology, leaving a critical gap in our understanding of their interrelated dynamics. This separation has limited our ability to predict and manage the impacts of changing sea urchin populations on seagrass ecosystems.

Mathematical modeling offers a powerful tool for bridging this knowledge gap. The Lotka-Volterra model, originally developed for predator-prey relationships, provides a framework for analyzing the complex interactions between producers and consumers in marine ecosystems. By adapting this model to the specific context of seagrass-sea urchin interactions, we can begin to understand the thresholds at which herbivory transitions from beneficial to destructive.

This study employedthe transect quadrant method for data collection, combining field observations with mathematical modeling to explore the critical threshold at which sea urchin populations begin to induce seagrass decline. Our approach integrates existing research on seagrass growth rates, sea urchin feeding behaviors, and population dynamics to create a comprehensive model of these interactions. By incorporating data from previous studies on seagrass growth patterns, sea urchin feeding rates, and survival metrics, we aimed to develop a predictive framework for understanding ecosystem stability.

The research goes beyond theoretical understanding, aiming to provide practical insights for marine conservation efforts. By identifying the specific conditions and population thresholds that lead to ecosystem degradation, this study seeks to develop effective strategies for maintaining the delicate balance between herbivore populations and seagrass ecosystem health **(Sutia *et al.*, 2021)**. Understanding these thresholds is crucial in ensuring that management interventions can effectively prevent the overgrazing of seagrass beds by sea urchins.

This integrated approach, combining field observations, existing ecological knowledge, and mathematical modeling, addresses fundamental questions about ecosystem stability and resilience. How do changes in sea urchin populations impact seagrass coverage over time? What are the critical thresholds signaling potential ecosystem collapse? By answering these questions, the study contributes to a deeper understanding of how these dynamics unfold, enabling better protection and management of vital marine ecosystems for future generations **(Moreira-Saporiti *et al.*, 2023)**. These findings can inform decision-making in coastal management and conservation, guiding efforts to prevent the collapse of seagrass meadows and to preserve marine biodiversity.

## MATERIALS AND METHODS

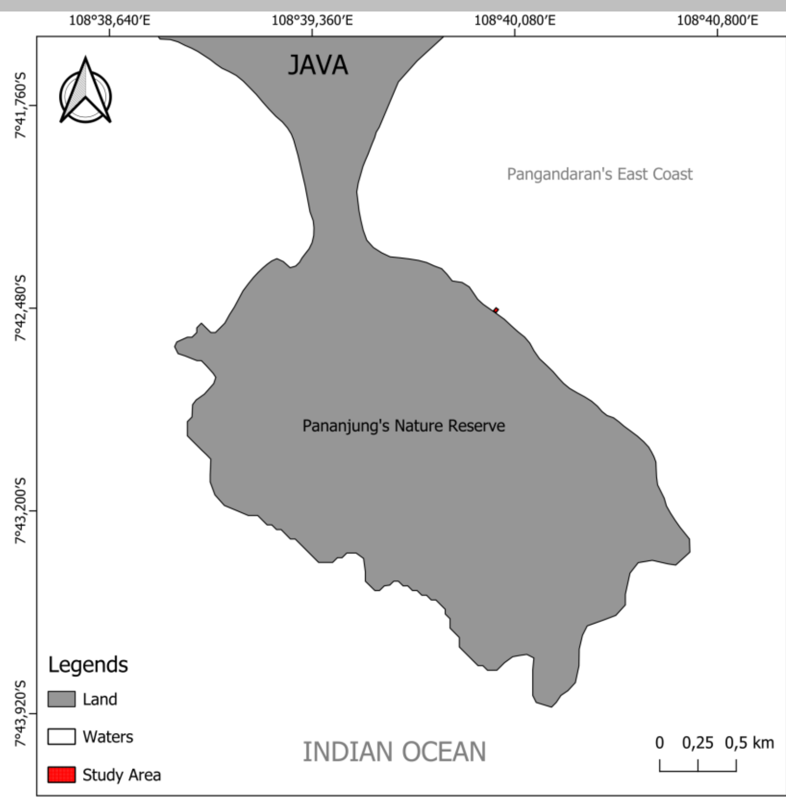


**Fig. 1.** Map of the study area

The study area, as shown in Fig. (1), is located in Pangandaran's Marine Protected Area (MPA), a designated section within Pananjung's Nature Reserve on Java Island, Indonesia. This area covers approximately 470 hectares of coastal ecosystem and is home to extensive seagrass meadows that provide critical habitats for a variety of marine species. The protected status of the area has allowed the ecosystem to remain relatively undisturbed, offering an ideal setting for examining the interactions between sea urchins and seagrass.

The site is characterized by a combination of sandy substrate and rocky outcrops, with water depths ranging from 0.5 to 3 meters during low tide. These environmental conditions provide a unique context for understanding the ecological balance between herbivores and seagrass, making it a valuable location for studying the population dynamics of sea urchins and their impact on seagrass meadows. The preservation of this area allows for the observation of natural processes and serves as a baseline for studying changes in ecosystem health over time.

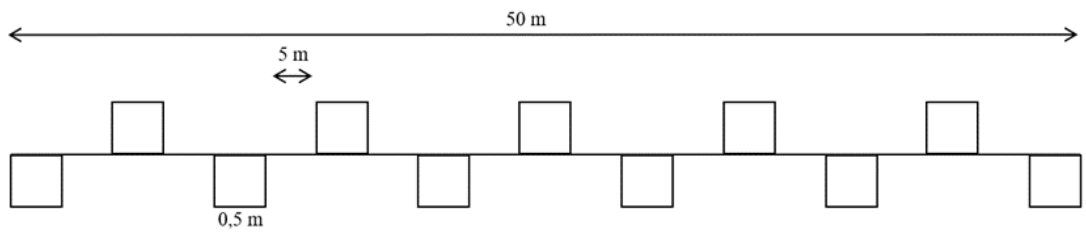


**Fig. 2.** Transect quadrants configuration

Field surveys were conducted between May 2024 and June 2024, encompassing transitional seasons to take into account for seasonal variations. The sampling design employed a systematic transect quadrant method **(Edgeloe *et al*., 2022; Nong *et al*., 2023)**, which was implemented during low tide conditions when tidepools naturally form. For each sampling session, a 50-meter transect line (Fig. 2) was placed parallel to the shoreline, with sampling points established every 5 meters along the line **(Martínez-Abrain, 2014)**. At each sampling point, 0.5 x 0.5 meter quadrants were positioned for detailed observation and measurement of the sea urchin population and seagrass coverage. This systematic approach allowed for consistent and thorough sampling of the study area.

Data collection was conducted twice daily—once in the morning from 07:00 to 09:00, and again in the afternoon from 15:00 to 17:00. This schedule was designed to capture any potential diurnal variations in the behavior and distribution of sea urchins, as their activity levels may differ between day and night. The sampling technique employed in this study is consistent with methods used in similar studies **(Nadiarti *et al.*, 2021; Harahap *et al.*, 2022; Moreira-Saporiti *et al*., 2023)**, ensuring the reliability and comparability of the results. Within each quadrant, the following parameters were measured:

$$\%C = \frac{Area\ occupied\ by\ species}{Total\ area} \times 100 \qquad (1)$$

$$D = \frac{Average\ count\ of\ species}{Total\ area} \qquad (2)$$

1. Seagrass coverage assessment: The percentage of seagrass cover %*C* was calculated using the equation (1) above.
2. Sea urchin density measurement: Sea urchin density (*D*) was determined using the equation (2) above **(Herliansyah *et al*., 2024)**.

To analyze the dynamic interaction between sea urchins and seagrass populations, a modified Lotka-Volterra predator-prey model was employed. The model consists of two coupled differential equations (3) and (4) **(Doust & Gholizade, 2014)**:

$$\frac{dx}{dt} = \alpha x - \beta y \quad (3)$$

$$\frac{dy}{dt} = \delta xy - \gamma y \quad (4)$$

Where:
*x* represents seagrass population density (percentage cover)
*y* represents sea urchin population density (individuals/m²)
*t* represents time (days)
*α* is the intrinsic growth rate of seagrass (day)
*β* is the herbivory rate coefficient (day)
*δ* is the sea urchin growth rate coefficient (day)
*γ* is the natural mortality rate of sea urchins (day)

To ensure data quality and reliability, several validation steps such as regular calibration of measurement tools and equipment, cross-validation of observations by multiple trained observers, photographic documentation of quadrants for verification purposes, and implementation of standardized data recording protocols were implemented. The study design and methodology were reviewed and approved by the institutional research ethics committee, and all necessary permits for conducting research within the marine protected area were obtained from relevant authorities.

## RESULTS AND DISCUSSION

**Table 1**. Seagrass coverage

| No. | Species | %C |
|---|---|---|
| 1 | *Cymodocea rotundata* | 18 |

The ecological survey revealed distinct patterns in both seagrass coverage and sea urchin populations within the study area. As shown in Table (1), *Cymodocea rotundata* demonstrated a coverage percentage of 18%, representing the dominant seagrass species in the ecosystem. This moderate coverage suggests that while the seagrass meadow maintains a presence, it may be experiencing pressure from various ecological factors including herbivory. The remaining 82% of the study area comprised a matrix of rock formations and sediment, creating a heterogeneous habitat structure that influences both seagrass establishment and sea urchin foraging patterns.

**Table 2.** Sea urchin density

| No. | Species | *D* |
|---|---|---|
| 1 | *Echinometra lucunter* | 8.73 |

The sea urchin population, dominated by *Echinometra lucunter*, exhibited a density of 8.73 individuals per square meter (Table 2). This density value provides crucial context for understanding the herbivory pressure on seagrass populations. When compared to similar studies in other tropical seagrass ecosystems **(Valentine & Heck, Jr., 1991; Alcoverro & Mariani, 2002)**, this density falls within a range that warrants careful monitoring, as it approaches levels that could potentially trigger significant ecosystem changes.

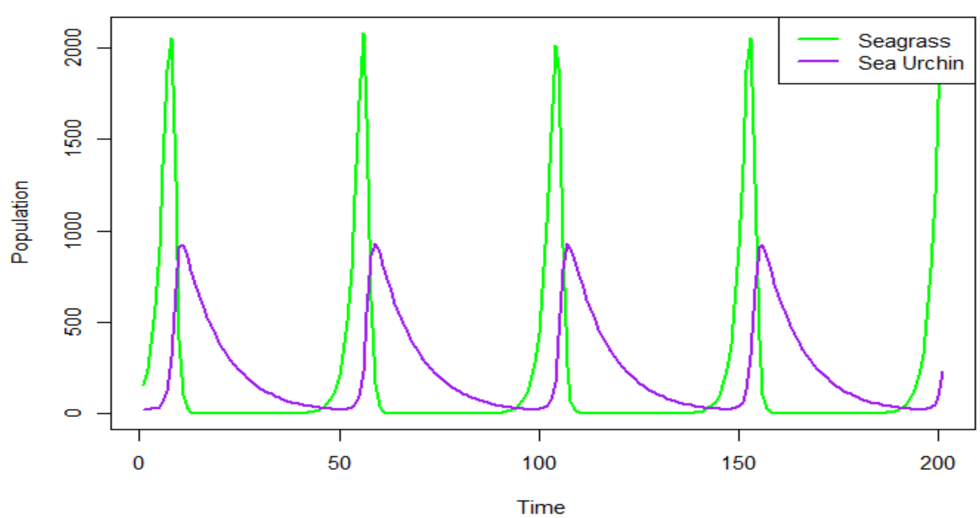


**Fig. 3.** Population dynamics graph over day; *x* axis units = Individual, *y* axis units units = Day

The population dynamics illustrated in Fig. (3) reveal complex interactions between seagrass and sea urchin populations over time. The initial conditions, with 153 seagrass individuals and 24 sea urchins within the 275m² study area, represent a starting point that appears stable but holds potential for rapid change. The temporal progression shows a concerning trend: the seagrass population experiences a gradual decline while sea urchin numbers increase, suggesting an imbalance in the ecosystem's regulatory mechanisms.

The simulation parameters $\alpha = 0.5$ for seagrass growth rate, $\beta = 0.002$ for sea urchin herbivory rate, $\gamma = 0.1$ for sea urchin mortality in absence of seagrass, and $\delta = 0.0005$ for sea urchin growth rate due to herbivory reveal several key insights about the system's behavior. The relatively high seagrass growth rate $\alpha$ indicates good potential for recovery under optimal conditions. However, this is counterbalanced by the herbivory rate $\beta$ which, though seemingly small, can lead to significant cumulative effects on seagrass populations over time.

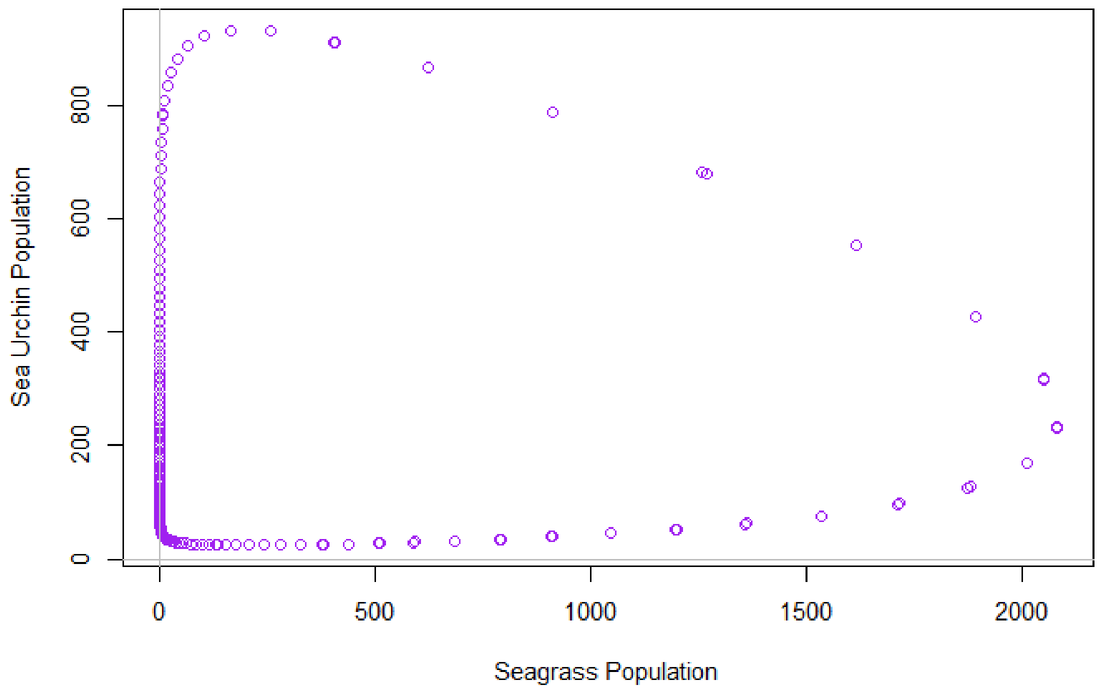


**Fig. 4.** Phase diagram; X axis units = Individual, Y axis units = Individual

The phase diagram (Fig. 4) provides crucial insights into the system's stability thresholds. The analysis indicates that the ecosystem approaches a critical tipping point when the sea urchin population nears 250 individuals. This threshold represents a crucial management benchmark, beyond which the system may transition into an alternative, less desirable state characterized by reduced seagrass coverage and potential ecosystem degradation.

The identification of this threshold has significant implications for ecosystem management. The model suggests that intervention should occur within 8 days of reaching certain population parameters to prevent irreversible damage to the seagrass meadow. This relatively short window emphasizes the importance of regular monitoring and rapid response capabilities in management protocols.

The findings of this study highlight the broader implications for ecosystem services provided by seagrass meadows. The observed relationship between sea urchin density and seagrass coverage suggests that any disruption to this balance can lead to cascading effects on several ecosystem functions. For example, a decline in seagrass coverage due to overgrazing could reduce the meadow's capacity to sequester carbon, thereby diminishing its role in mitigating climate change. Additionally, the loss of seagrass affects habitat availability for marine species that rely on it for shelter and breeding grounds, which could threaten biodiversity. Furthermore, a reduction in seagrass coverage may lead to increased sediment mobilization, negatively affecting water quality and coastal protection services.

Based on the simulation results and observed population dynamics, several management recommendations have emerged. First, it is essential to implement regular monitoring programs to track both sea urchin density and seagrass coverage, with particular attention to areas approaching the identified threshold of 250 sea urchins per study area. Second, it is crucial to establish clear intervention protocols that can be activated within an 8-day window when population dynamics indicate that threshold conditions are approaching. These proactive measures, such as controlling sea urchin populations, can help prevent irreversible damage to the ecosystem.

While this study provides valuable insights, several important research gaps remain. There is a need for extended temporal studies to better understand the long-term stability of these ecosystems under various environmental conditions. Further investigation into how seasonal and climatic variations affect the interaction between sea urchins and seagrass populations would also be beneficial. Additionally, more precise quantification of population thresholds under different environmental conditions is necessary to improve management decision-making. Lastly, studies focusing on the recovery potential of seagrass meadows following overgrazing events and the factors that influence successful restoration are essential for ensuring the long-term resilience of these ecosystems. Addressing these research gaps will enhance our understanding and support the development of more effective management practices for maintaining healthy seagrass ecosystems.

## CONCLUSION

This study offers a comprehensive analysis of the complex relationship between seagrass ecosystems and sea urchin populations, focusing specifically on the interaction between *Cymodocea rotundata* and *Echinometra lucunter*. By combining rigorous field observations with mathematical modeling using the Lotka-Volterra framework, the research uncovers critical insights into the delicate balance that sustains these vital coastal ecosystems. The study demonstrates that sea urchin herbivory plays a key role in shaping seagrass community dynamics, but this relationship operates within narrow ecological thresholds. When sea urchin populations are below certain levels, their grazing activity can actually promote ecosystem health by preventing overgrowth and maintaining biodiversity. However, the mathematical models reveal a critical tipping point at approximately 250 individual sea urchins, beyond which their grazing can trigger a catastrophic decline in seagrass coverage.

Temporal analysis of the interaction between sea urchins and seagrass highlights an important early intervention window. This window occurs within the first eight days of detecting population changes, underscoring the need for regular monitoring and rapid response protocols in coastal management strategies. Identifying these specific thresholds and temporal windows equips ecosystem managers with practical guidance for implementing preventive measures before irreversible system degradation occurs.

The study emphasizes that maintaining stable seagrass ecosystems requires a sophisticated understanding of both biological interactions and environmental factors. Successfully preserving these valuable marine habitats depends on the ability to implement timely interventions, which are based on careful monitoring and a deep understanding of population dynamics. The use of Lotka-Volterra models has proven to be valuable in identifying the exact conditions where consumer-producer relationships shift from stable to unstable states.

While the findings of this research are significant for immediate application in coastal management, the study also identifies several areas that require further investigation. Additional empirical data collection and refinement of the models are necessary to better understand how different environmental factors influence the sea urchin-seagrass dynamic. Future studies should aim to validate the theoretical thresholds observed in this study across different geographical locations and under various environmental conditions.

The implications of this work extend beyond immediate ecosystem management challenges. As coastal environments face increasing pressure from climate change and human activities, understanding these core ecological relationships is crucial for developing resilient conservation strategies. The mathematical frameworks and management guidelines presented in this study lay a foundation for protecting essential marine habitats, while also highlighting the need for continuous adaptation and refinement of conservation approaches as new data and emerging challenges arise.

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