DEPARTMENT OF MARINE SCIENCES

Sustainable Management and Resilience of Eelgrass Meadows *(Zostera marina)* in Kalmar County, Sweden: Local Strategies for Ecosystem Conservation

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Abstract

Eelgrass (*Zostera marina*) meadows are foundational components of shallow coastal ecosystems in the Baltic Sea, providing critical ecological functions such as habitat provision, nutrient cycling, and shoreline stabilization. However, these meadows are under increasing pressure from environmental stressors including eutrophication, habitat degradation, and climate change. This study investigates the spatial patterns and ecological drivers of eelgrass distribution in Kalmar Sound, Sweden, with a focus on two representative sites: Köpingsvik and Stora Rör. Using a suite of biophysical indicators—including salinity, water temperature, Secchi depth, dissolved oxygen, and nutrient concentrations—we assessed environmental conditions and related them to eelgrass coverage and structure. In parallel, a governance analysis based on stakeholder interviews and SWOT evaluation identified institutional strengths, weaknesses, and opportunities for conservation.

Findings show that water quality, especially light penetration and nutrient load, is a key determinant of eelgrass vitality at Köpingsvik, whereas Stora Rör appears influenced by more complex, site-specific factors. Evidence of pondweed encroachment suggests ecological transitions that may indicate long-term habitat deterioration. While Kalmar County benefits from long-standing monitoring programs and stakeholder networks, implementation gaps persist in restoration practices and strategic adaptation to climate-related risks.

This study highlights the importance of localized ecological data and context-specific governance to support adaptive management. By combining ecological monitoring with participatory approaches and policy alignment, Kalmar County can enhance the resilience of eelgrass meadows.

Popular Scientific Summary

Safeguarding Underwater Meadows – Eelgrass in Kalmar Sound

Eelgrass meadows, formed by the marine plant *Zostera marina*, are often referred to as the rainforests of the sea. These underwater habitats play a vital role in supporting marine life, cleaning the water, and storing carbon. Along Sweden's Baltic coast, especially in Kalmar County, these meadows are both ecologically important and increasingly vulnerable.

In recent decades, eelgrass has been declining due to human activities such as agriculture, pollution, and coastal development. One major problem is eutrophication too many nutrients entering the sea which leads to algal blooms that block sunlight and suffocate seafloor habitats.

This study investigated eelgrass meadows at two sites in Kalmar Sound—Köpingsvik and Stora Rör—to better understand how environmental factors like water clarity, temperature, and nutrient levels affect eelgrass health. It found that water quality, especially light availability and nutrient concentrations, strongly influences where eelgrass can grow. It also revealed local changes, such as the spread of competing plants, which may signal long-term ecosystem shifts.

Besides the ecological analysis, the study also looked at how local authorities and stakeholders are working to protect these meadows. While Kalmar County has a good foundation for managing coastal environments, challenges remain—such as coordinating actions, securing funding, and adapting to climate change.

The future of eelgrass in the Baltic Sea depends on both scientific understanding and political action. With the right strategies, local engagement, and sustainable management, Kalmar County could become a model region for marine conservation in Sweden and beyond.

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1 Introduction

Eelgrass (*Zostera marina*) is a marine flowering plant that forms extensive underwater meadows in shallow coastal waters, predominantly in temperate regions such as the Baltic Sea. It creates extensive underwater meadows in shallow waters, thriving in sandy or muddy substrates with moderate salinity and adequate light (Yu et al., 2023).These meadows are among the most productive and ecologically significant marine habitats, providing crucial ecosystem services including sediment stabilization, water filtration, carbon sequestration, and habitat provision for diverse marine fauna like juvenile fish and invertebrates (Boström et al., 2014; Duarte et al., 2008; Hemminga & Duarte, 2000). The conservation of eelgrass is therefore essential for maintaining coastal ecosystem health and resilience, as well as for supporting fisheries and coastal livelihoods.

Despite their importance, eelgrass meadows have suffered substantial declines globally, with the Baltic Sea being a notable hotspot of degradation (Moksnes et al., 2016). These losses are primarily driven by environmental stressors such as eutrophication, coastal development, overfishing, and climate change impacts, which reduce water quality and alter trophic dynamics, thereby threatening the survival of eelgrass habitats (Boström et al., 2014; Eklöf et al., 2012; Moksnes et al., 2021). In Sweden, regions like Bohuslän have experienced up to 60% loss of eelgrass meadows, highlighting the urgent need for effective conservation strategies (Nyqvist et al., 2009).

In the Baltic Sea, including areas such as Kalmar County, signs of degradation are evident, with declining water quality and nutrient over-enrichment contributing to habitat loss, although monitoring records are often shorter or inconsistent (Eriander, 2016). Restoration and conservation of eelgrass meadows have therefore become key priorities in marine spatial planning, national action plans, and under the EU Water Framework Directive (SwAM, 2017).

While losses of *Zostera marina* in Sweden have been partially attributed to known environmental stressors, understanding the full scope and underlying causes of these changes requires comprehensive, long-term ecological monitoring. Effective conservation not only depends on identifying where and why eelgrass is declining, but also on tracking the key environmental parameters that influence its health and distribution (Orth et al., 2006; Boström et al., 2014; Roca et al., 2016). As such, recent research emphasizes the importance of using biophysical indicators—such as salinity, temperature, water clarity (e.g., Secchi depth), dissolved oxygen, chlorophyll-a, and nutrient concentrations (e.g., DIN, DIP, TN, TP)—to assess the ecological status of eelgrass meadows (Carstensen et al., 2011; Björk et al., 2008).

At the same time, there is growing recognition that long-term resilience hinges on effective governance frameworks and stakeholder engagement, highlighting the need for an integrated socio-ecological approach to seagrass conservation (Grech et al., 2011; Santos et al., 2021). To address these knowledge gaps, this study applies a suite of ecological indicators widely recognized in seagrass monitoring to evaluate the environmental conditions influencing *Zostera marina*. These indicators—salinity, water temperature, Secchi depth, dissolved oxygen, chlorophyll-a, and nutrient concentrations (DIN, DIP, TN, TP)—are essential for capturing the physical and chemical conditions that shape eelgrass distribution and resilience. Their selection is grounded in both international monitoring frameworks and scientific recommendations for adaptive, data-informed coastal management (Carstensen et al., 2011; Teixeira et al., 2016).

Building on this framework, the selection of abiotic indicators—such as water temperature, salinity, nutrient concentrations, and dissolved oxygen—follows established approaches for ecological assessment, where physical and chemical parameters are used to quantify environmental stressors and habitat quality (Feld et al., 2010). These indicators are particularly valuable in marine monitoring, where direct biological assessments may be limited by spatial or temporal constraints. In this study, these variables are used alongside structural indicators of *Zostera marina* (coverage and depth) to provide a comprehensive evaluation of ecological status and potential stressors.

In Sweden, various management frameworks and policies have been developed at the local, national, and regional levels to protect and restore coastal ecosystems, including eelgrass meadows. Nationally, initiatives such as the Action Plan for Eelgrass Meadows (SwAM, 2017) and participation in the HELCOM Baltic Sea Action Plan (HELCOM, 2021) emphasize nutrient reduction, habitat restoration, and sustainable marine use. Locally, counties such as Kalmar have engaged in eelgrass monitoring, established Marine Protected Areas (MPAs), and implemented site-specific measures aimed at reducing anthropogenic stressors (SwAM, 2015; Havs- och vattenmyndigheten, 2017).

However, effective seagrass management extends beyond policy implementation. It requires the integration of ecological data with governance mechanisms that are adaptive, participatory, and context specific. Research has shown that management success often hinges on how well local institutions incorporate scientific insights, stakeholder knowledge, and spatial planning (Björk et al., 2008; Grech et al., 2011; Unsworth et al., 2015). For example, maintaining water quality, protecting intact eelgrass meadows, and regulating coastal activities such as dredging, anchoring, and nutrient runoff are crucial for building ecosystem resilience, particularly in the face of climate change and intensifying human pressures.

Despite ongoing restoration and protection efforts, challenges persist—especially in aligning scientific monitoring with on-the-ground management needs. In the Baltic Sea, including Kalmar County, this misalignment is partly due to historical gaps in long-term monitoring, which limit the availability of reliable biodiversity data to guide local decisions. Kahlert et al. (2020) emphasized that while scientific assessments often highlight biodiversity monitoring as a major gap, stakeholders may prioritize different concerns such as regulatory clarity, enforcement, or funding. Bridging this gap requires governance approaches that recognize both ecological complexity and the socio-political landscape.

To explore these dynamics, this study adopts an integrated approach that combines ecological and governance perspectives. First, it analyses spatial patterns in *Zostera marina* distribution in Kalmar Sound in relation to key abiotic indicators (e.g., salinity, temperature, dissolved oxygen, nutrients), which reflect the environmental conditions shaping seagrass health. Second, it evaluates local management practices by conducting a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis based on stakeholder perspectives, aiming to assess the effectiveness and adaptability of current eelgrass conservation strategies in Kalmar County.

To guide this dual focus on ecological assessment and governance evaluation, the study is structured around two central research questions:

1.1 Research Objectives

1. To what extent do spatial patterns in *Zostera marina* distribution in Kalmar Sound reflect key ecological drivers, and how can these patterns inform evidence-based marine management in Kalmar County?

2. What are the strengths, weaknesses, opportunities, and threats associated with current eelgrass conservation strategies in Kalmar County, as perceived by local stakeholders?

These questions aim to capture both the environmental conditions influencing eelgrass health and the institutional capacities shaping its management, providing a comprehensive basis for future policy and conservation efforts.

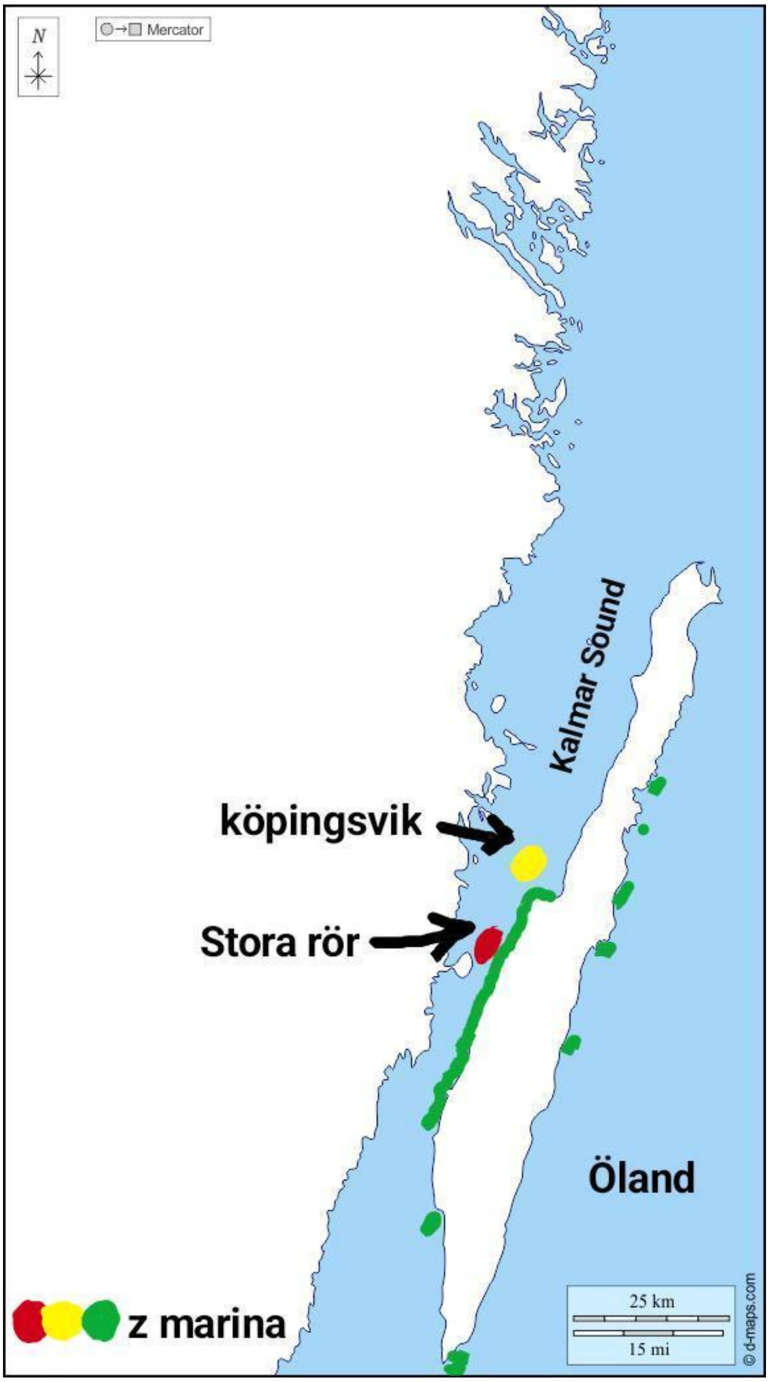
1.2 Study Site: Kalmar County

Kalmar County, located along Sweden's Baltic coast, is a critical region for eelgrass (Zostera marina) conservation due to its extensive and relatively robust seagrass meadows. Local authorities in Kalmar have implemented conservation and monitoring efforts for over two decades, providing valuable long-term data on eelgrass distribution, health, and ecological trends (Havs- och vattenmyndigheten, 2017).

The total eelgrass area along the Swedish Baltic coast is estimated to range between 60 and 130 km², with meadows generally becoming smaller and more fragmented towards the west coast of Öland because of decreasing salinity (Boström et al., 2003; Tobiasson, 2023, personal communication). Despite the challenging low salinity conditions (5–6 PSU) and competition from freshwater plants, Kalmar Sound supports some of the largest and most ecologically significant eelgrass populations in the region (Boström et al., 2014). These meadows typically occur at depths of 2.5 to 4 meters, with records extending to 8 meters, and provide essential habitat for diverse marine species while contributing to nutrient cycling and ecosystem stability (Boström et al., 2014).

This study focuses on two representative eelgrass sites within Kalmar Sound: Stora Rör and Köpingsvik (see Fig 1). Both sites function as critical nurseries and nutrient sinks, supporting local biodiversity and coastal ecosystem functioning (Ahlgren, 2016; Tobiasson, 2023). Long-term monitoring has revealed spatial and temporal variability in eelgrass coverage at these sites, with some areas maintaining stable populations while others have declined due to factors like increased competition from invasive species such as pondweed (Tobiasson, 2023). These dynamics underscore the importance of understanding the ecological drivers and governance contexts that influence eelgrass resilience in Kalmar County.

Figure 1 Map of study area in Kalmar County, Sweden



The map shows the location of Kalmar County and the two study sites, Stora Rör and Köpingsvik, on the eastern side of Kalmar Sound. Green areas represent the total distribution of Zostera marina in the region, while the yellow and red areas indicate the specific study sites. Data sources: Boström et al. (2014) and Tobiasson (2023). Map created by the author.

2 Methods

This study employs an interdisciplinary, empirical framework integrating ecological science with environmental governance. Zostera marina (eelgrass) is used as a key bioindicator species due to its sensitivity to environmental changes and its role in assessing coastal ecosystem health (Orth et al., 2006). The framework is grounded in marine ecosystem assessment principles, highlighting long-term ecological monitoring paired with stakeholder engagement to guide conservation (Waycott et al., 2009).

This approach facilitates a holistic understanding of the socio-ecological system surrounding eelgrass in Kalmar County, providing actionable insights for improved ecosystem management and policy.

Alongside the ecological focus, social science methods are incorporated via SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis to systematically evaluate current conservation and management strategies, including institutional and policy factors affecting eelgrass protection (Helms & Nixon, 2010). This dual perspective captures the complex interactions between ecological conditions and governance in coastal environments.

By combining quantitative ecological data with qualitative governance evaluation, this mixed-methods study addresses the multifaceted challenges of eelgrass conservation, linking empirical trends to social and policy contexts.

2.1 Data Collection

2.1.1 Ecological Data

Quantitative ecological data were compiled from multiple sources to capture temporal trends in Zostera marina coverage and depth distribution. Coverage and depth data were extracted from Kalmar County’s environmental monitoring reports spanning two decades (2004–2023), providing a longitudinal dataset essential for detecting patterns and potential declines.

Complementary environmental variables were obtained from Sweden’s national aquatic database (https://www.sverigesvattenmiljo.se/), which offers standardized, high-quality measurements consistent across time and space. Based on prior research indicating critical drivers of eelgrass health (Duarte, 1991; Baden et al., 2003).

In addition, to address the second research question, a qualitative approach was employed using a SWOT analysis based on stakeholder perspectives. Data were collected through email questionnaires, which, although less interactive than in-person interviews, allowed for thoughtful and detailed responses. The initial questionnaire was sent to Kalmar County authorities, followed by a second set of questions to gain deeper insights into the management and conservation of Zostera marina in the region. The questionnaire and the anonymized responses are included in the annex (Appendix A) for reference.

2.1.2 Water-Quality Monitoring Parameters and Their Role in Zostera marina Assessments

As per Carstensen et al. (2011), a comprehensive coastal monitoring strategy includes multiple physical and chemical parameters that serve as indicators of environmental quality and ecological health. These parameters are particularly relevant in monitoring seagrass habitats such as Zostera marina, which are sensitive to water clarity, nutrient levels, and oxygen availability etc.

1.Salinity

Salinity is measured using the Practical Salinity Scale (PSS), indicates the salt content in water and is commonly assessed with conductivity sensors like CTD probes, which also record temperature and depth. In the context of Zostera marina, salinity is important because this eelgrass species grows best in moderately saline environments. Changes in salinity can cause stress to the plants and may affect where they can survive and thrive (Nejrup & Pedersen, 2008). Monitoring salinity helps understand the habitat conditions that support healthy eelgrass populations

2.Temperature

Water temperature controls many biological and chemical processes in aquatic environments. It affects metabolic rates, the breakdown of organic matter, oxygen levels, and nutrient cycling. For Zostera marina, temperature is especially important because the growth and seasonal patterns of eelgrass depend on it. Higher temperatures can reduce the plant’s productivity and make it more susceptible to diseases (Niu et al., 2012).

3.Seechi Depth

Transparency, or water clarity, is measured using tools like the Secchi disk or PAR (Photosynthetically Active Radiation) sensors. It indicates how much light penetrates the water, which is vital for photosynthesis. For Zostera marina, light availability is a key factor limiting its growth and depth range. When water clarity is low—often due to phytoplankton blooms or suspended sediments—eelgrass cannot grow as deeply or as densely. Transparency is typically assessed through Secchi disk readings or by measuring how light decreases with depth (Benson et al., 2013).

4.Dissolved Oxygen

Dissolved Oxygen (DO) measures the amount of oxygen present in the water, reflecting the balance between processes like photosynthesis and respiration within the ecosystem. Low DO levels, or hypoxia, often signal nutrient pollution and eutrophication. For Zostera marina, adequate oxygen is critical, especially in bottom sediments where the eelgrass roots respire; low oxygen conditions can harm root health and overall plant survival (Raun & Borum, 2013).

5. Chlorophyll-a

Chlorophyll-a is a pigment found in phytoplankton and is commonly used as an indicator of phytoplankton biomass in aquatic systems. High chlorophyll-a concentrations often signal increased algal growth, which can result from nutrient enrichment (eutrophication).

In the context of Zostera marina, elevated chlorophyll-a levels can reduce water clarity by promoting phytoplankton blooms, which limit light penetration—a critical factor for eelgrass photosynthesis and growth (Blindow et al., 2014). Therefore, monitoring chlorophyll-a helps assess the risk of light limitation and potential stress on eelgrass beds caused by nutrient-driven algal proliferation.

6. Nutrients

For this study, nutrient monitoring focused on four key parameters: Total Nitrogen (TN) measured in winter, Dissolved Inorganic Phosphorus (DIP), Dissolved Inorganic Nitrogen (DIN), and Total Phosphorus (TP) measured in winter. These parameters are widely recognized in Zostera marina assessments because they effectively indicate nutrient loading and eutrophication potential, which directly affect eelgrass health through algal shading and competition for light (Devlin & Brodie, 2023). Winter measurements of TN and TP are particularly useful as they represent baseline nutrient levels before the growing season, providing insight into nutrient accumulation and potential stressors for Z. marina.

2.1.3 Email Interview

Email interviewing is a qualitative data collection method involving asynchronous exchanges of questions and answers via email, allowing participants to respond thoughtfully at their convenience (Pell et al., 2020). This method was chosen to engage key informants from Kalmar County's marine management community, who are geographically dispersed and comfortable with electronic communication. The initial set of open-ended questions (see Annexure A) captured broad insights into eelgrass distribution and management challenges. Responses were followed up with personalized, iterative emails to clarify and deepen understanding of emerging themes. This approach facilitated rich, reflective data and enabled ongoing analysis during data collection, enhancing the quality of findings (Bowker & Tuffin, 2004; Corbin & Morse, 2003).

Email interviews offer advantages such as flexibility, cost-effectiveness, and readily available written records (Opdenakker, 2006). However, they also have limitations, including the absence of non-verbal cues and the risk of brief responses (Burns, 2010; Jemielniak, 2020). To maximize data depth, this study combined open-ended questions with follow-up inquiries to encourage fuller participant engagement. The collected responses were analyzed using SWOT analysis, described in the following section, to identify strengths, weaknesses, opportunities, and threats related to eelgrass conservation and management in Kalmar Sund.

2.2 Data Processing and Analysis

Raw field and environmental data were initially cleaned and organized in Microsoft Excel to ensure consistency, handle missing values, and remove outliers. The refined datasets were then imported and analysed in both Excel and GraphPad Prism 10 where comprehensive statistical analyses were performed to investigate relationships between environmental variables and the spatial distribution of Zostera marina in Kalmar Sund.

To address the first research question — exploring the extent to which the spatial distribution of Zostera marina reflects underlying ecological conditions — several statistical approaches were employed to identify and quantify relevant associations:

2.2.1 Correlation Analysis

While not used as a primary analytical tool, the concept of correlation informed interpretation of variable associations in regression outputs. Correlation measures the strength and direction of linear relationships and helped indicate which environmental parameters (e.g., temperature, salinity, depth) showed preliminary associations with eelgrass distribution. However, correlation does not imply causation and may be influenced by confounding factors (Schober et al., 2018).

2.2.2 Simple Linear Regression

To isolate and understand the effect of individual environmental variables on Z. marina distribution, simple linear regression was used. Separate models were built with Z. marina coverage (%) and depth as dependent variables against environmental predictors such as salinity, temperature, and light availability. This approach helps assess whether specific abiotic factors are significantly associated with spatial patterns of seagrass (James et al., 2023).

2.2.3 Multiple Linear Regression (MLR)

To capture the combined influence of ecological conditions, multiple linear regression models were developed. These incorporated two or more independent variables (e.g., salinity, temperature, turbidity) to predict Z. marina coverage and depth. This multivariate approach is especially relevant to marine management, as it reflects the complexity of habitat suitability and allows for the identification of key environmental drivers (Eberly, 2007). Variables were screened for multicollinearity and assumptions of normality, linearity, and homoscedasticity were assessed before model interpretation.

2.2.4 Paired t-test

To further evaluate how benthic vegetation composition varied across study sites, a paired t-test was used to compare Z. marina coverage with that of co-occurring pondweed (Stuckenia pectinata). This test assessed whether observed shifts in species dominance could be statistically supported, offering additional insight into ecological responses to environmental stressors (Ruxton, 2006). By integrating these statistical tools, the analysis provides a robust basis for evaluating how environmental variables shape eelgrass distribution and how this information can inform evidence-based management strategies in Kalmar County’s coastal ecosystems.

2.2.5 SWOT Analysis

SWOT analysis is a strategic planning tool used to identify and evaluate the internal Strengths and Weaknesses of an organization or system, as well as the external Opportunities and Threats it faces (Helms & Nixon, 2010). This framework helps to systematically assess factors that can influence the success or failure of a project, policy, or management strategy.

In this study, SWOT analysis is used to capture the perspectives of key stakeholders involved in eelgrass (Zostera marina) conservation in Kalmar Sound. By organizing insights into strengths, weaknesses, opportunities, and threats, it provides a structured understanding of current conservation practices, challenges, and potential areas for improvement. This qualitative approach complements the ecological data by addressing governance and management dimensions critical for effective ecosystem protection.

The primary participant in the study was the Kalmar County ecologist responsible for eelgrass conservation, whose institutional expertise offered a comprehensive understanding of the current management practices. The questionnaire used in the research was developed based on Sweden’s Zostera marina National Action Plan and encompassed a range of topics, including the conservation strategies currently in place, monitoring protocols and the challenges associated with them, the implementation and enforcement of relevant policies, as well as the participant’s insights into the perceived barriers and successes in eelgrass protection. This approach allowed for an in-depth exploration of both practical and policy-related aspects of eelgrass conservation within Kalmar County.

A follow-up questionnaire clarified initial responses and allowed for expansion on critical points. Thematic analysis was conducted to categorize findings under the SWOT framework, revealing strengths, weaknesses, opportunities, and threats relevant to eelgrass governance in the region. Respondent anonymity was maintained, and summarized results are included in Appendix A.

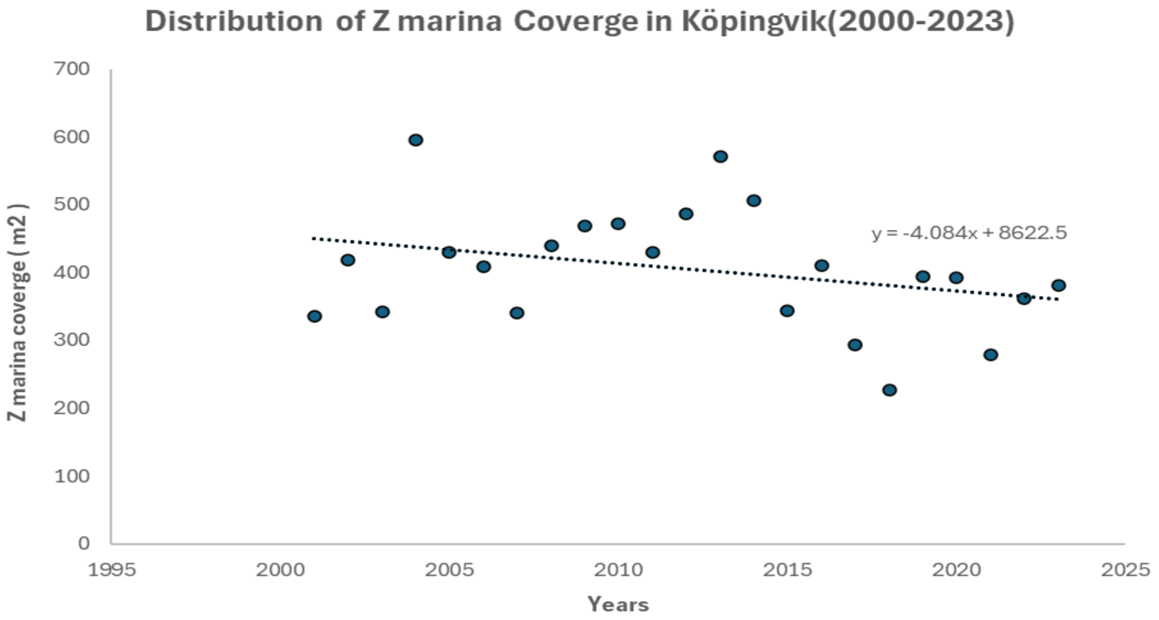
3 Results

This chapter explores the spatial distribution of Zostera marina (eelgrass) in Kalmar Sund, emphasizing the ecological factors that affect its presence, including light availability and nutrient concentrations. The results are situated within a wider ecological context, underscoring eelgrass as a crucial indicator of the health of coastal ecosystems. Furthermore, a SWOT analysis is conducted to evaluate the strengths, weaknesses, opportunities, and threats associated with the conservation of eelgrass in the area. This analysis seeks to guide effective marine management strategies and promote sustainable conservation efforts through interdisciplinary cooperation.

3.1 Long-Term Trends in *Zostera marina* Coverage

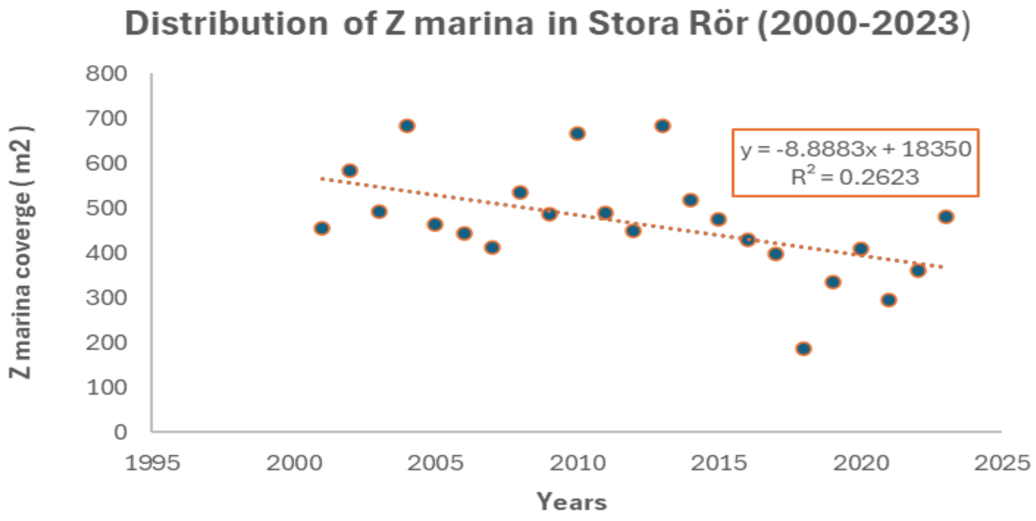
Long-term monitoring shows changes in *Zostera marina* coverage across the Köpingsvik and Stora Rör regions from 2000 to 2023. Trends and comparisons between sites are illustrated in Figures 2, 3, and 4.

Figure 2 Temporal Trend in Zostera marina Coverage at Köpingsvik (2000–2023)



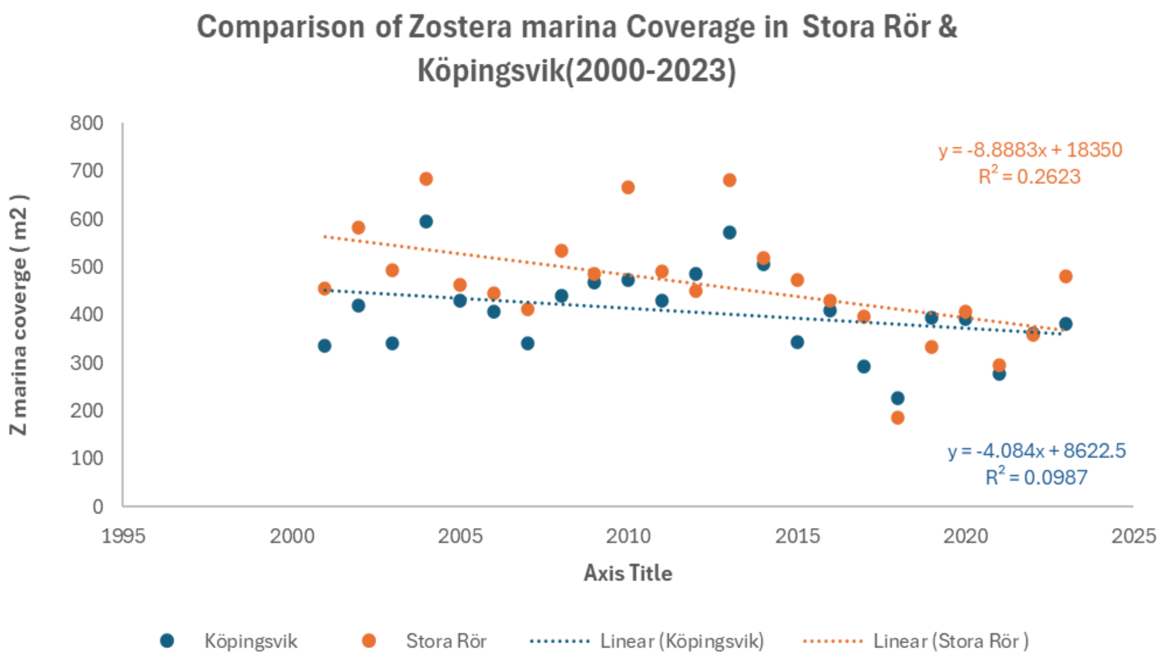
Line plot illustrating changes in Zostera marina coverage at the Köpingsvik site from 2000 to 2023. Each point represents the mean coverage (%) recorded each year. Source of data: Tobiasson (2023). The slope of the regression line was –4.08, (p = 0.144), Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).

Figure 3 Temporal Trend in Zostera marina Coverage at Stora Rör (2000–2023)



Time series showing annual Zostera marina coverage at the Stora Rör site over 23 years. Each point denotes observed percent coverage per year. Source of data: Tobiasson (2023). The slope of the regression line is significantly different from zero (p = 0.01), confirming a statistically significant declining trend in eelgrass coverage over time at Stora Rör. Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).

Figure 4 Comparison of Zostera marina Coverage Between Köpingvik and Stora Rör (2000–2023)



The scatter plot displays the mean eelgrass (Zostera marina) coverage (m²) at Köpingvik and Stora Rör over a 23-year period. Each point represents an individual yearly measurement of eelgrass coverage at the respective site. This visualization highlights the distribution and variability of eelgrass coverage through time at both locations, allowing comparison of trends and data spread. Source of data: Tobiasson (2023) & Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).

Fig 4 shows that Z marina coverage is declining in both the sites over time. The rate of decline was steeper at Stora Rör (slope =-8.89) compared to Köpingsvik (slope= -4.08), in indicating a more rapid loss of seagrass at Stora Rör. However, the r square value was relatively low for both the locations Stora Rör $R^2 = 0.26$, Köpingsvik $R^2 = 0.10$. In addition, a Pearson correlation analysis between Z marina coverage at the two locations revealed a strong positive correlation (r = 0.82).

3.2 Correlation Between Environmental Parameters and Zostera marina Coverage at Stora Rör

Pearson correlation analyses were conducted to assess the relationship between eight water quality parameters and the coverage of *Zostera marina* at Stora Rör (see Figure 5). None of the correlations were statistically significant (all $p > 0.05$), indicating no strong linear associations between eelgrass coverage and the environmental parameters examined. The strongest correlation observed was a weak negative association with Secchi depth (r = –0.30, R^2 = 0.09, p = 0.18), while the weakest was with winter Total Nitrogen (r = –0.00, $R^2 \approx 0.00$, p = 1.00). Other parameters showed weak and non-significant correlations:

- Temperature: r = –0.27, p = 0.23
- Chlorophyll-a: r = 0.14, p = 0.55
- Dissolved Inorganic Phosphorus (DIP): r = 0.19, p = 0.42
- Dissolved Inorganic Nitrogen (DIN): r = –0.01, p = 0.96
- Salinity: r = –0.03, p = 0.89
- Winter Total Phosphorus: r = –0.11, p = 0.6

3.3 Correlation Between Water Quality Parameters and *Zostera marina* Coverage in Köpingvik

Pearson correlation analyses were performed to evaluate the relationships between nine water quality parameters and the coverage of *Zostera marina* in the Köpingvik region (refer to Figure 6). Among these, Dissolved Inorganic Nitrogen (DIN) showed the strongest statistically significant correlation, revealing a strong negative association (r = –0.67, R^2 = 0.45, p = 0.001). A moderate positive correlation was also found with Secchi depth (r = 0.61, R^2 = 0.37, p = 0.003), indicating that clearer water is linked to higher eelgrass coverage. A statistically significant moderate negative correlation was observed with Chlorophyll-a (r = –0.56, R^2 = 0.31, p = 0.009), suggesting that higher phytoplankton concentrations may reduce eelgrass distribution.

Other parameters showed weak or negligible, and statistically non-significant, correlations with eelgrass coverage:

- Total Nitrogen (winter): r = –0.30, R^2 = 0.09, p = 0.19
- Temperature: r = –0.10, p = 0.67

- Salinity: r = 0.12, p = 0.62
- Total Phosphorus (winter): r = 0.02, p = 0.93
- Oxygen: r = –0.07, p = 0.75
- Dissolved Inorganic Phosphorus (DIP): r = –0.00, p = 0.99

Figure 5 Correlation between Environmental Parameters and Zostera marina Coverage in the Stora Rör Region

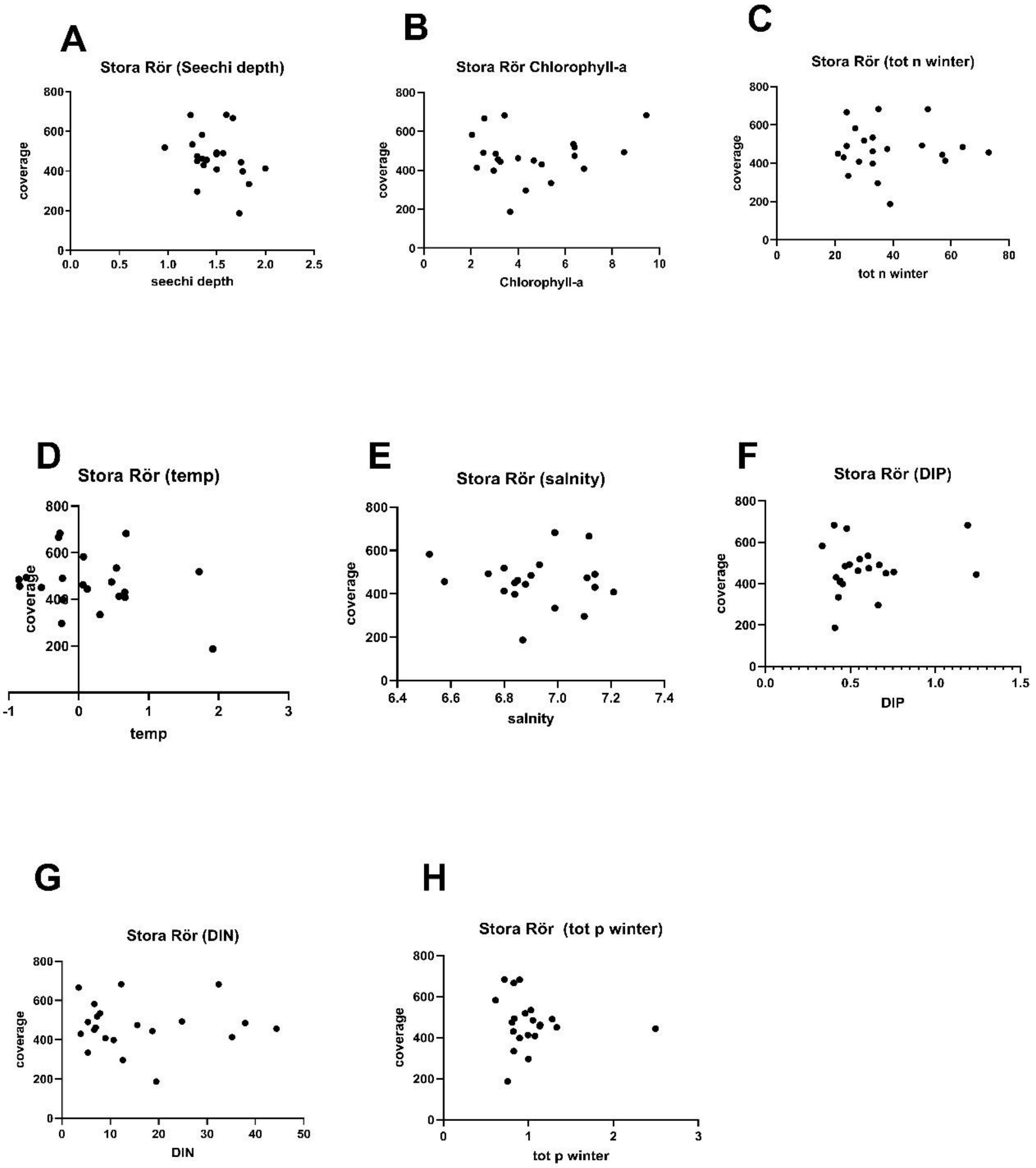


Figure 5 A-H: *Relationship Between Environmental Parameters and Coverage of Zostera marina in Stora Rör. The scatter plots depict the relationships among different environmental factors (Secchi*

depth, Chlorophyll-a, Total Nitrogen, Temperature, Salinity, DIP, DIN, and Total Phosphorus during Winter) and the coverage of Zostera marina in the Stora Rör area. Each data point is indicated by a black dot, and Pearson correlation analysis was employed to evaluate these relationships. Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).

Figure 6 . Correlation Between Environmental Parameters and Zostera marina Depth in the Köpingvik Region.

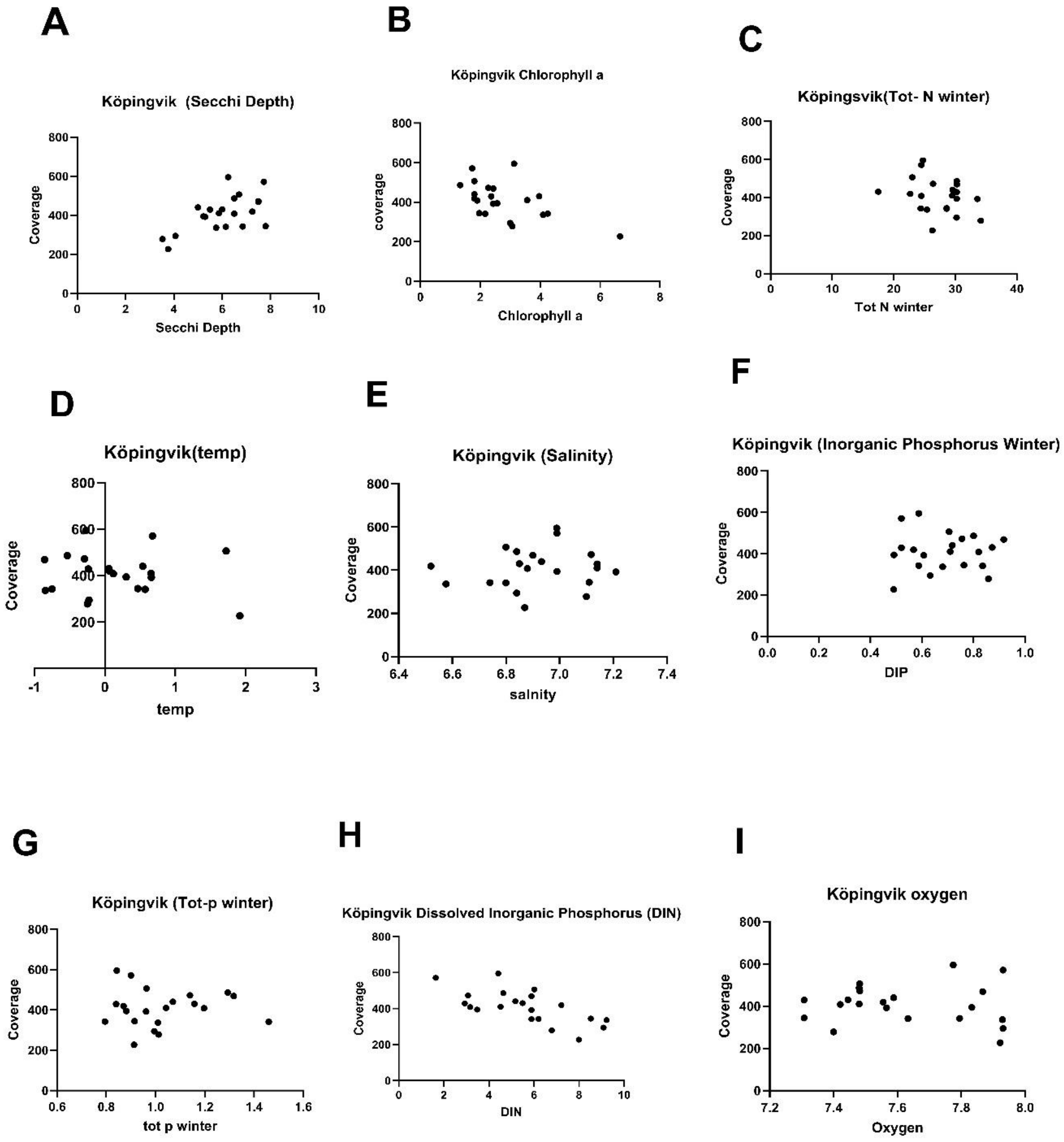


***Figure 6 A–I**: Relationship Between Environmental Parameters and Depth of Zostera marina in Köpingvik. Scatter plots present the associations between environmental conditions (e.g., Secchi depth, Chlorophyll-a, DIP, DIN, Total Nitrogen, Temperature, Salinity, and Winter*

Total Phosphorus) and the coverge of Zostera marina. Pearson correlation coefficients were calculated, and each black dot represents an individual data point. Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).

3.4 Multiple Linear Regression Analysis of *Zostera marina* Coverage in the Köpingvik Region

A multiple regression analysis assessed the influence of Secchi depth, Chlorophyll-a, and DIN on *Z. marina* coverage. The model was significant (F (3,17) = 10.26, p = 0.0004, $R^2 = 0.64$), indicating that 64% of the variation in coverage was explained (see fig 7 & 8).

The regression equation was:

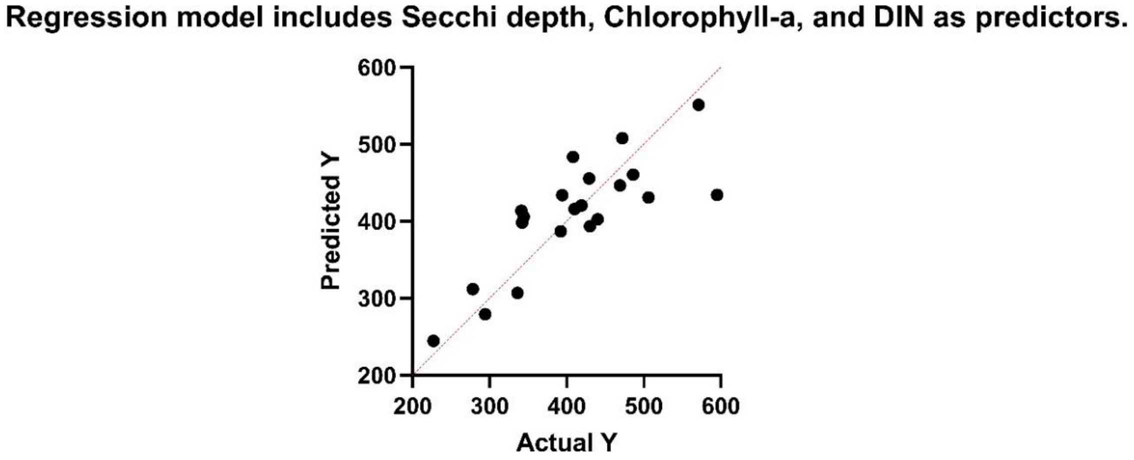
$Coverage = 27.1 \times Secchi - 13.5 \times Chl\text{-}a - 20.9 \times DIN + Intercept$

Secchi depth (p = 0.04) and DIN (p = 0.01) were significant predictors, while Chlorophyll-a was not (p = 0.32). Residuals showed acceptable normality, and no multicollinearity was detected (VIF < 1.5).

Secchi depth was a significant positive predictor (B = 27.1, p = 0.04), implying higher water clarity is associated with greater seagrass coverage. DIN showed a significant negative relationship (B = -20.9, p = 0.01), indicating that increasing nutrient concentrations are linked to reduced coverage. Chlorophyll-a was not a significant predictor (B = -13.5, p = 0.32) and did not contribute meaningfully when included with the other variables.

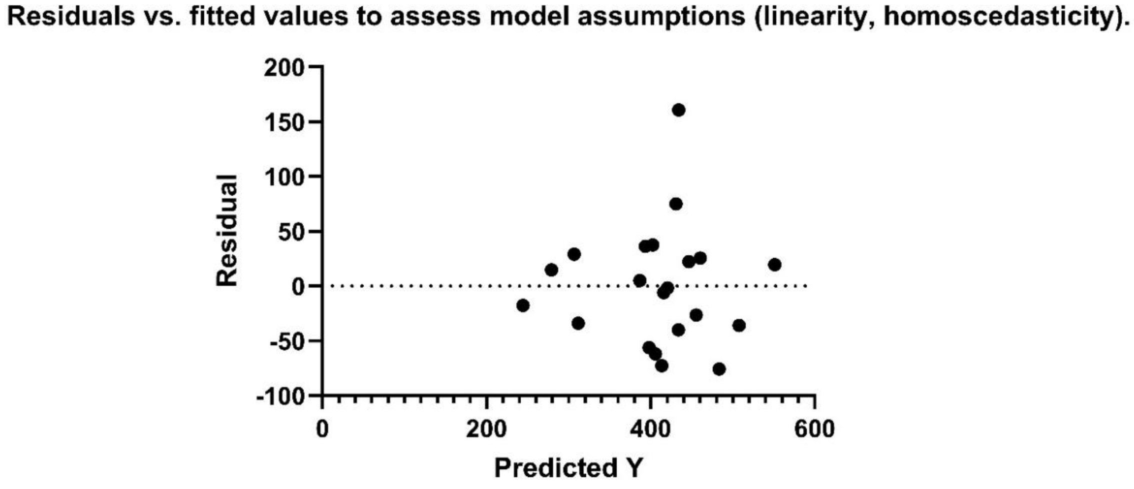
VIF values for all predictors were below 1.5, indicating no multicollinearity. While residuals passed most normality tests, the D’Agostino-Pearson test showed some deviation (p = 0.01). Given regression’s robustness to mild normality violations, results remain valid.

Figure 7 Actual vs. Predicted Zostera marina Coverage in Köpingvik Based on Multiple Linear Regression



The regression model used Secchi depth, chlorophyll-a, and DIN to predict eelgrass coverage (%). The scatterplot compares observed vs. predicted values with a 1:1 reference line; points above indicate underestimation, below indicate overestimation. The model was significant overall (p < 0.05), though not all predictors were individually significant. Data source: Sveriges vattenmiljö.

Figure 8 Residual Plot for Multiple Linear Regression Model Predicting Zostera marina Coverage in Köpingvik



This plot displays residuals versus fitted values to assess key model assumptions, including linearity and homoscedasticity. Each point represents the difference between observed and predicted eelgrass coverage at a given fitted value. The random scatter of residuals around the *horizontal reference line (y = 0) suggests that the assumptions of linearity and constant variance (homoscedasticity) are reasonably met, with no apparent systematic patterns or trends.*

3.5 Multiple Linear Regression Analysis of Zostera marina Coverage in the Stora Rör

A multiple linear regression analysis was conducted to explore how Dissolved Inorganic Phosphorus (DIP) and Secchi depth predict *Zostera marina* coverage in the Stora Rör region (refer to Figures 8 & 9). These variables were selected based on prior correlations with seagrass coverage.

The overall regression model was not statistically significant, $F(2,18) = 1.11$, $p = 0.35$, with an R^2 of 0.11, indicating that only 11% of the variation in coverage was explained by these predictors combined.

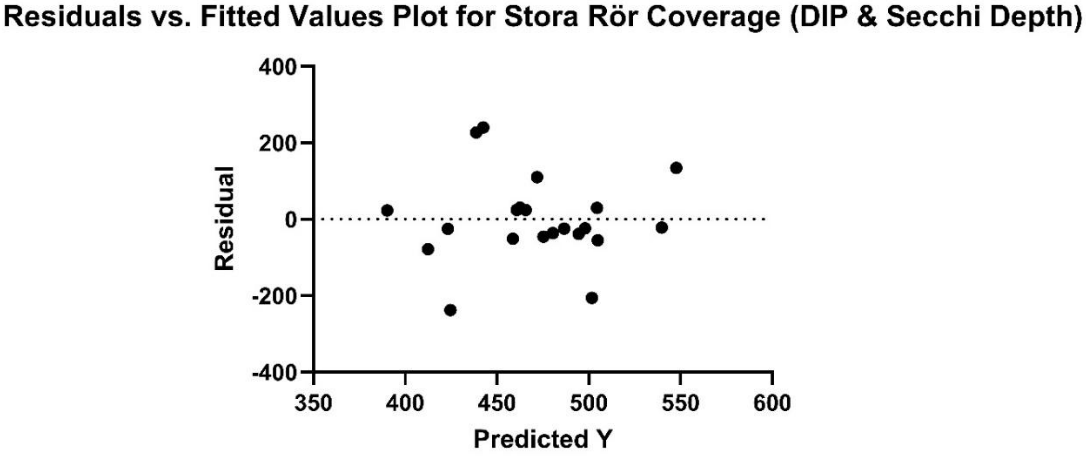
The intercept was significant ($B = 633$, $p = 0.004$), but neither DIP ($B = 70$, $p = 0.55$) nor Secchi depth ($B = –137$, $p = 0.24$) were significant predictors. This suggests that DIP and Secchi depth do not meaningfully influence seagrass coverage in Stora Rör when modeled together.

Variance inflation factors for both predictors were below 1.5, indicating no multicollinearity. Residual normality tests showed some deviations (Anderson-Darling $p = 0.02$, Kolmogorov-Smirnov $p = 0.02$), though Shapiro-Wilk and D'Agostino-Pearson tests passed.

Residual vs. fitted plots (Figure 9) and actual vs. predicted plots (Figure 10) indicated limited explanatory power and supported model assumptions.

Overall, DIP and Secchi depth do not significantly predict *Z. marina* coverage in Stora Rör within this model.

Figure 9 Residual Plot for Stora Rör Coverage



Residuals versus fitted values are shown to assess key model assumptions, including linearity and homoscedasticity. The model includes dissolved inorganic phosphorus (DIP) and Secchi depth as predictors. The random distribution of residuals around the horizontal line (y = 0) suggests the model does not exhibit strong deviations from linearity or constant variance. *Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).*

3.6 Correlation Between Zostera marina Depth and Environmental Parameters in the Stora Rör Region

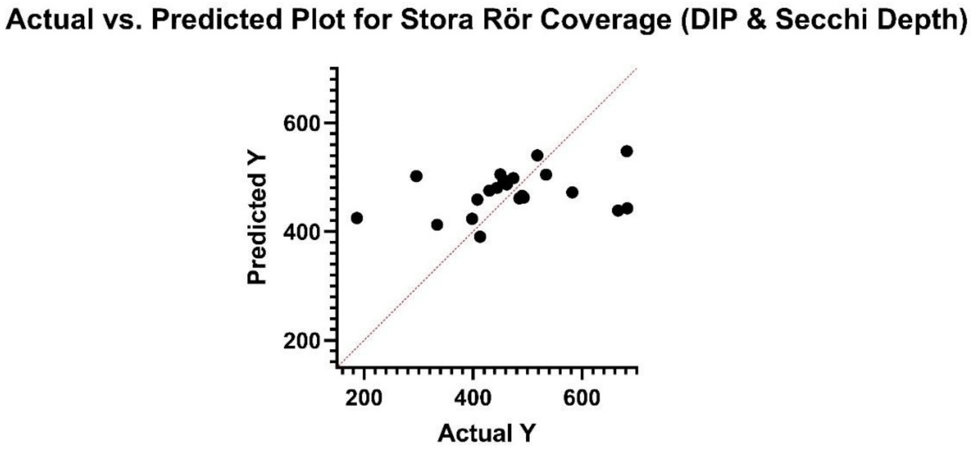
Pearson correlation analyses evaluated the relationship between *Zostera marina* depth and eight environmental factors in the Stora Rör area (see Figure 11). Among these, Secchi depth and Dissolved Inorganic Phosphorus (DIP) showed statistically significant correlations, while other factors had weak or negligible non-significant associations (see fig 11 &13).

Secchi depth was moderately negatively correlated with seagrass depth (r = –0.56, R^2 = 0.31, p = 0.04), indicating that clearer water is associated with shallower *Z. marina* growth. Conversely, DIP showed a moderate positive correlation (r = 0.56, R^2 = 0.32, p = 0.04), suggesting higher phosphorus levels correspond with deeper seagrass occurrences. Confidence intervals for both excluded zero, supporting their significance.

Other parameters, including Chlorophyll-a (r = –0.03, p = 0.93), Total Nitrogen winter (r = –0.08, p = 0.78), Temperature (r = 0.21, p = 0.47), Salinity (r = –0.12, p = 0.69), Total Phosphorus winter (r = 0.13, p = 0.65), and Dissolved Inorganic Nitrogen (r = –0.06, p = 0.84), showed no significant correlations, with confidence intervals including zero.

These results indicate that in Stora Rör, seagrass depth is significantly associated only with water clarity and phosphorus levels, reflecting the balance of light availability and nutrient conditions influencing habitat suitability along the depth gradient.

Figure 10 Actual vs Predicted Plot for Stora Rör Coverage



Actual versus predicted values are plotted to evaluate the performance of the regression model, which includes dissolved inorganic phosphorus (DIP) and Secchi depth as predictors. The closeness of points to the 1:1 line indicates the model's predictive accuracy. Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).

Figure 11 Correlation between depth of Zostera marina meadows and environmental parameters in the Stora Rör

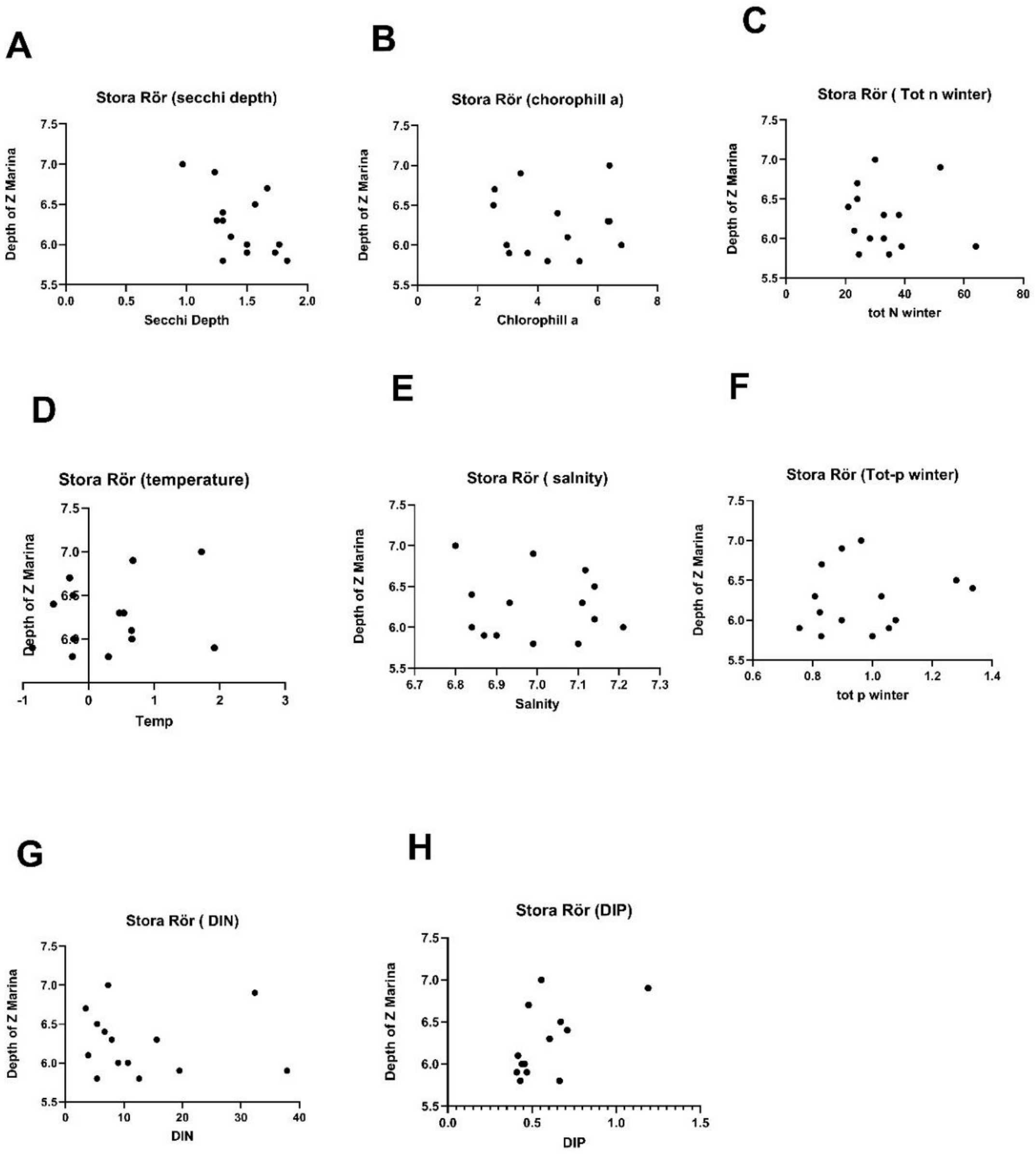
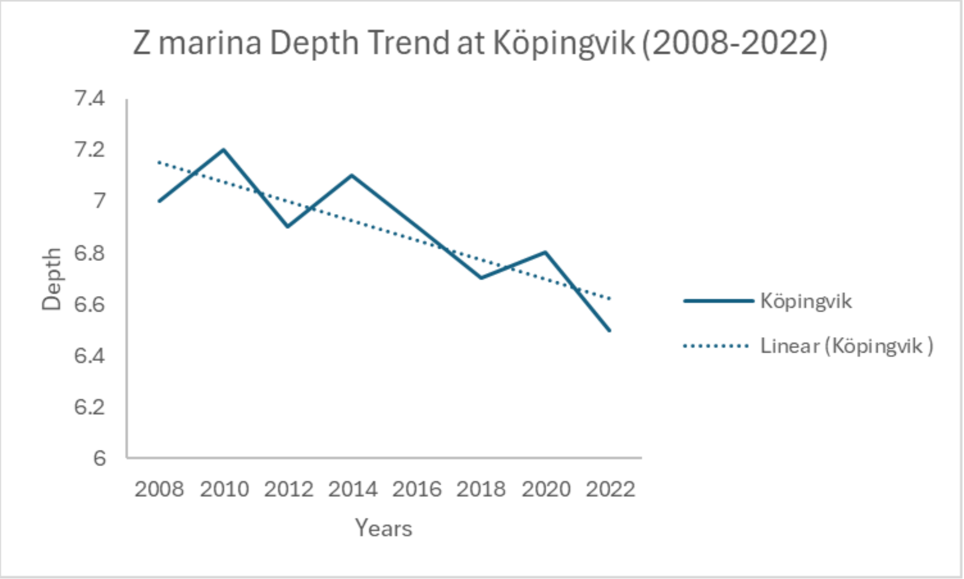


Figure A–H: *Correlation Between Environmental Factors and Zostera marina Depth in Köpingvik. The scatter plots illustrate the relationships between various environmental parameters, including Secchi depth, Chlorophyll-a, Dissolved Inorganic Phosphorus (DIP), Dissolved Inorganic Nitrogen (DIN), Total Nitrogen, Temperature, Salinity, and Winter Total Phosphorus, and the depth at which Zostera marina is found. Pearson correlation coefficients have been computed, with each black dot indicating a specific data point. Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).*

Figure 12 Zostera marina Maximum Depth Trends at Köpingvik (2008–2022)



This line graph illustrates the annual maximum depth (in meters) of Zostera marina observed at the Köpingvik site from 2008 to 2022. The declining trend over time suggests a possible reduction in water clarity or other stressors limiting light penetration, which could be indicative of ecological degradation affecting eelgrass habitat depth limits. Source of data: Tobiasson (2023).

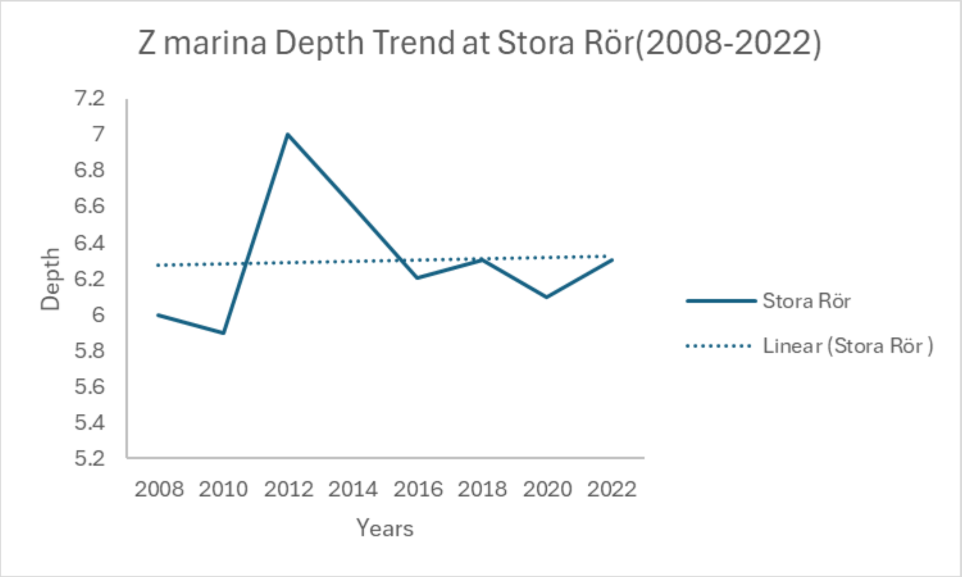
3.7 Correlation Between Zostera marina Depth and Environmental Parameters in the Köpingvik Region

A Pearson correlation analysis examined relationships between *Zostera marina* depth and environmental factors in the Köpingvik area (see Figure 13). Dissolved Inorganic Nitrogen (DIN) showed a significant negative correlation with seagrass depth (r = –0.61, p = 0.02), indicating higher DIN levels are associated with shallower eelgrass growth.

Other factors such as Secchi depth (r = 0.49, p = 0.08), winter Total Phosphorus (r = 0.30, p = 0.30), and winter Total Nitrogen (r = –0.29, p = 0.31) showed moderate but non-significant correlations. Temperature, salinity, Dissolved Inorganic Phosphorus (DIP), and oxygen did not display significant relationships with seagrass depth (refer fig 12 &14).

These results indicate that DIN concentrations may significantly influence the depth distribution of Z. marina in the Köpingvik area, while the other variables measured seem to have a lesser impact based on this dataset**.**

Figure 13 . Zostera marina Maximum Depth Trends at Stora Rör (2008–2022)



The figure displays the maximum recorded depth of Zostera marina at Stora Rör between 2008 and 2022. Fluctuations are evident, with a general downward trend suggesting reduction in depth colonization possibly due to deteriorating environmental conditions such as increased turbidity or nutrient enrichment. Source of data: Tobiasson (2023).

Figure 14 . Correlation Between Environmental Factors and Zostera marina Depth in the Köpingvik

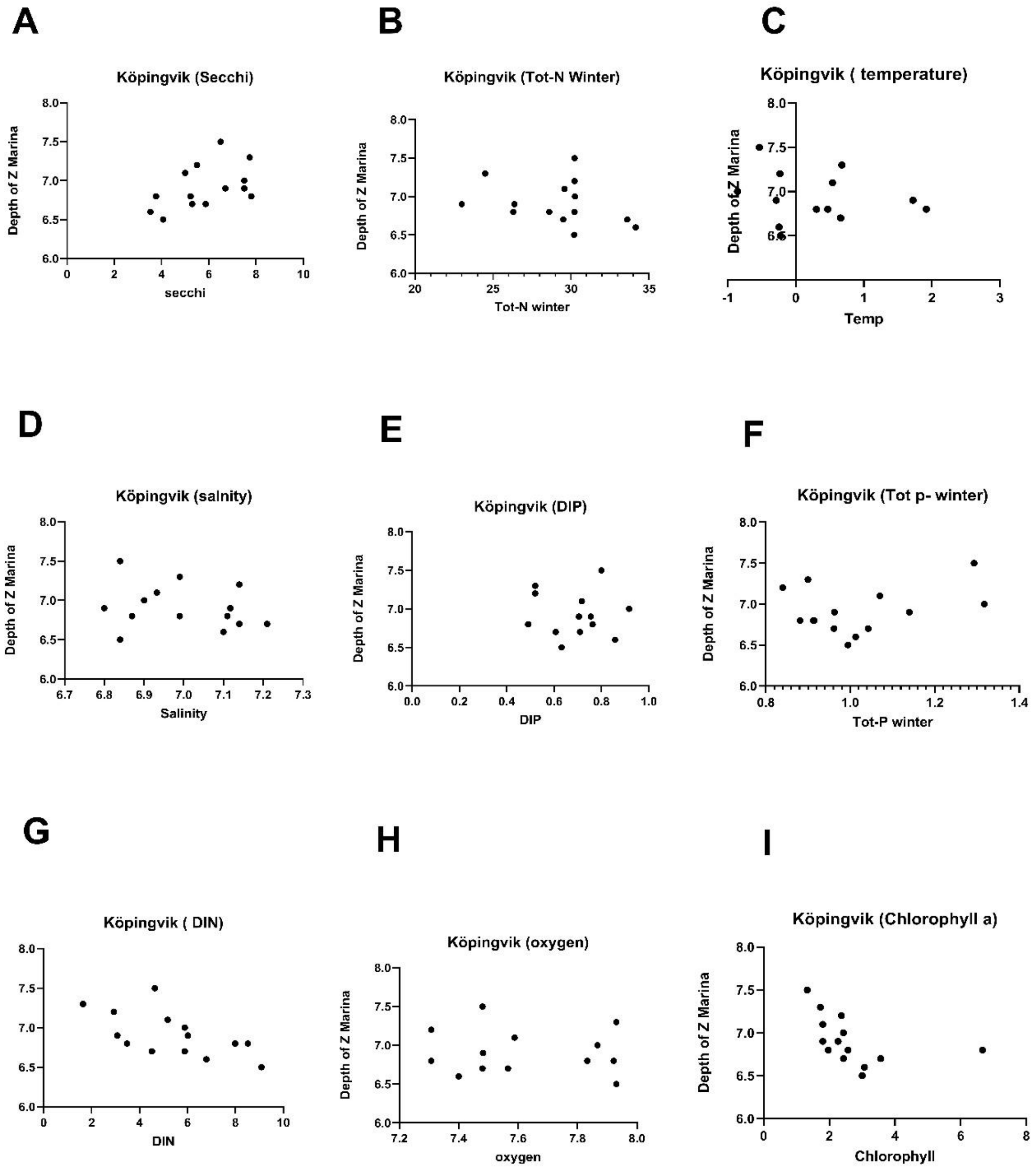


Figure A–H: *Association Between Environmental Factors and Zostera marina Depth in Köpingvik. The scatter plots illustrate the relationships between the depth of Z. marina and several environmental factors, such as Secchi depth, Chlorophyll-a, Total Nitrogen (Winter), Temperature, Salinity, Dissolved Inorganic Phosphorus (DIP), Dissolved Inorganic Nitrogen (DIN), and Total Phosphorus (Winter). Each black dot signifies an individual data point. Pearson correlation analysis was utilized to assess these associations. Source of data: Sveriges vattenmiljö (https://www.sverigesvattenmiljo.se/).*

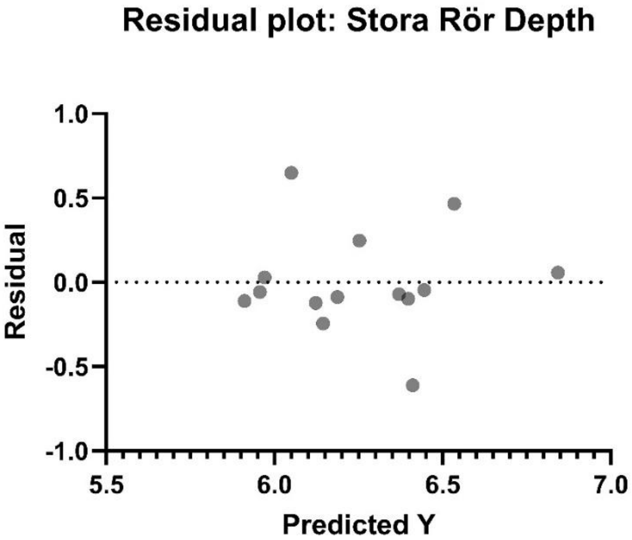
3.8 Multiple Linear Regression Analysis of *Zostera marina* Depth in the Stora Rör Region

A multiple linear regression was performed to assess how Secchi depth and Dissolved Inorganic Phosphorus (DIP) predict the depth distribution of *Zostera marina* in the Stora Rör area (Figures 15 & 16). The model was statistically significant (F(2,11) = 4.06, p = 0.05) and explained 42.5% of the variation in seagrass depth ($R^2 = 0.42$).

Individually, neither predictor was significant: DIP showed a positive trend (B = 0.74, p = 0.17), and Secchi depth a negative trend (B = –0.61, p = 0.18). Variance inflation factors were below 1.5, indicating no multicollinearity issues. Most normality tests for residuals were passed, except the Anderson-Darling test showed slight deviation (p = 0.03), but the model remains interpretable.

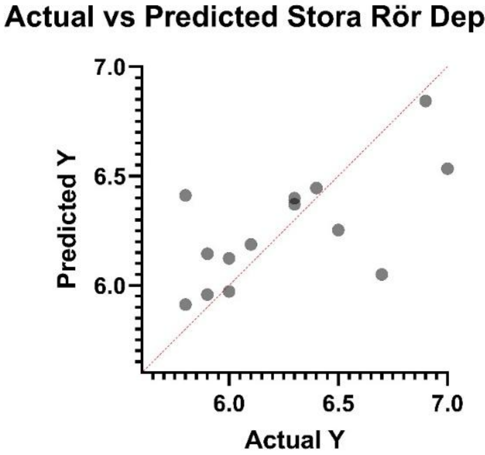
Figures 15 and 16 illustrate a moderate fit between observed and predicted values, and residuals appear randomly distributed, supporting linearity and homoscedasticity assumptions. These results suggest that while DIP and Secchi depth together explain some variation in *Z. marina* depth, neither has a statistically significant independent effect.

Figure 15 Residual Plot for Stora Rör depth



Residuals are plotted against predicted values to assess model assumptions, including linearity and homoscedasticity. The model includes depth as a predictor of Zostera marina coverage. A random scatter of residuals around zero suggests that these assumptions are reasonably met.

Figure 16 Actual vs Predicted Plot for Stora Rör depth



This figure compares observed coverage values with those predicted by the regression model using depth as the sole predictor. A close alignment of points along the 1:1 line indicates good model fit and predictive performance.

3.9 Multiple Linear Regression Analysis of *Zostera marina* Depth in the Köpingvik Region

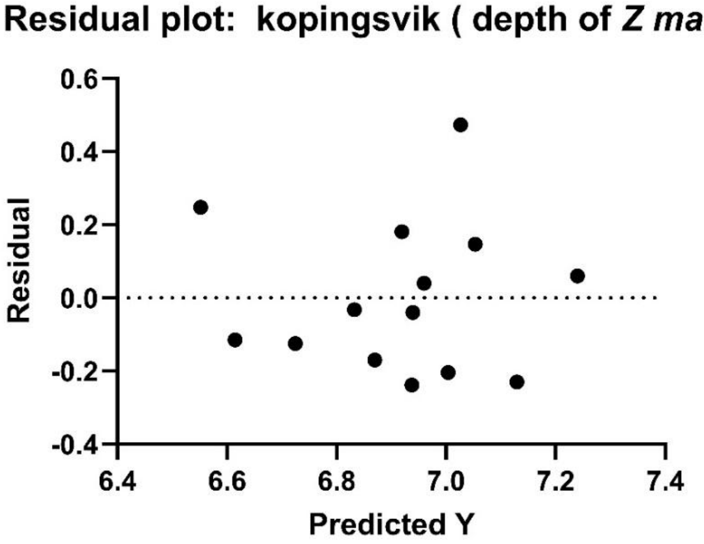
Multiple Linear Regression Analysis of *Zostera marina* Depth in the Köpingvik Region A multiple linear regression was conducted to evaluate the influence of Dissolved Inorganic Nitrogen (DIN), Secchi depth, and Chlorophyll-a on *Zostera marina* depth in Köpingvik (Figures 16 & 17). The model approached significance (F(3,10) = 2.76, p = 0.10) and explained 45% of the variance in seagrass depth ($R^2 = 0.45$).

None of the predictors were individually significant: DIN (B = –0.06, p = 0.11), Secchi depth (B = 0.04, p = 0.48), Chlorophyll-a (B = –0.03, p = 0.63). DIN showed the strongest negative trend, suggesting higher nutrient levels may relate to shallower seagrass depth.

No multicollinearity was detected (VIF < 2), and residuals met normality assumptions across all tests. Figures 17 and 18 show a reasonable fit between predicted and observed values, with residuals randomly distributed, supporting linearity and homoscedasticity.

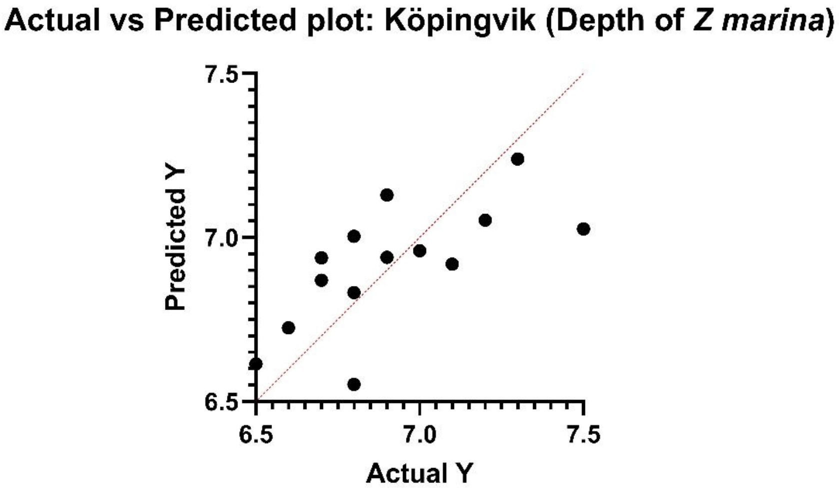
These findings suggest that while these variables may influence *Z. marina* depth, none significantly predict it independently in this model.

Figure 17 Residual Plot Köpingvik depth



Residuals are plotted against fitted values to assess model assumptions, including linearity and homoscedasticity. This diagnostic helps evaluate the adequacy of depth as a single predictor for eelgrass coverage in Köpingvik.

Figure 18 Actual vs Predicted Plot for the Köpingvik depth



The plot compares observed and predicted values from a simple linear regression model using depth as the sole predictor, illustrating the model's performance in explaining eelgrass coverage variability at Köpingvik.

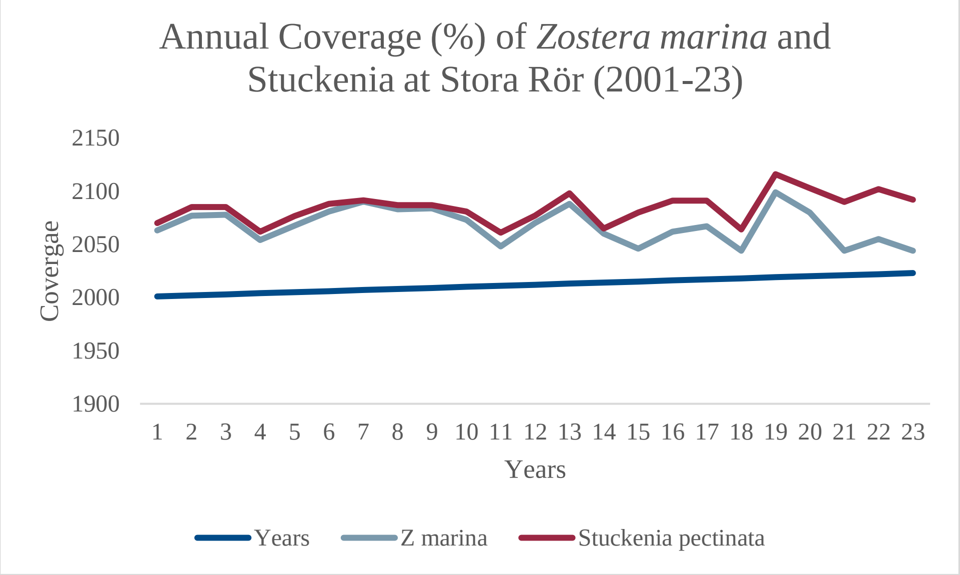
3.10 Comparison of *Zostera marina* and Pondweed (*Stuckenia pectinata*) Coverage at Stora Rör

Coverage of *Zostera marina* (eelgrass) and *Stuckenia pectinata* (pondweed) is compared over 23 years at Stora Rör (Figure 19). The test showed a significant difference between species coverage, t(22) = 5.94, p < 0.0001, with pondweed coverage on average 40 percentage points lower than eelgrass (mean difference = –39.7, 95% CI: –53.6 to –25.8), indicating eelgrass's dominance over time.

A strong negative correlation between their coverages was found (Spearman's r = –0.66, p = 0.0010; paired t-test r = –0.77), suggesting an inverse relationship. As eelgrass declined recently, pondweed increased, indicating a possible replacement (see fig 18)

The pairing explained about 62% of the variation ($R^2 = 0.62$), supporting the idea that pondweed has increasingly occupied space vacated by eelgrass in shallow areas at Stora Rör.

Figure 19 Paired Comparison of Zostera marina and Pondweed (Stuckenia pectinata) Coverage at Stora Rör



This line graph illustrates the yearly coverage percentages of *Zostera marina* and pondweed at Stora Rör from 2000 to 2022, highlighting the inverse trend in their abundance. *Source of data: Tobiasson (2023).*

A paired t-test revealed a significant difference in coverage between *Zostera marina* and *Stuckenia pectinata* across 23 years at Stora Rör, *t*(22) = 5.94, *p* < 0.0001. The mean difference was –39.71 percentage units (95% CI: –53.59 to –25.84). A strong negative correlation was observed between the two species over time (Spearman's $r = –0.66$, $p = 0.0006$; paired test $r = –0.77$). The effect size was large ($R^2 = 0.62$). A statistically significant difference was found (p < 0.0001), with pondweed coverage increasing as Z. marina declined over time.

3.11 Correlation Analysis of Zostera marina and Stuckenia pectinata Coverage

A Pearson correlation analysis was conducted to evaluate the relationship between the coverage of Zostera marina and pondweed (S. pectinata) in the Stora Rör region (refer to Figure 19). The analysis yielded a correlation coefficient of r = -0.7743, indicating a strong negative association between the two species' coverage.

The negative correlation suggests that as the coverage of Zostera marina decreases, the coverage of pondweed tends to increase, and vice versa, consistent with a competitive or replacement dynamic between the two species.

The significance of the correlation was tested using a t-test for correlation, resulting in a p-value < 0.001, confirming that the observed correlation is statistically significant and unlikely to have occurred by chance.

3.12 SWOT Analysis

This section presents the findings from the qualitative SWOT analysis conducted through semi-structured interviews with stakeholders involved in eelgrass (Zostera marina) conservation in Kalmar County. Interview responses were thematically coded according to four categories: strengths, weaknesses, opportunities, and threats. The following tables summarize the emergent themes and representative evidence from the interviews

3.12.1 Summary of Coded SWOT Themes from Interviews

This section provides a summary of the primary themes derived from stakeholder interviews, organized into Strengths, Weaknesses, Opportunities, and Threats (SWOT). Through a methodical coding of the qualitative data, consistent patterns and insights were identified to gain an understanding of stakeholder views on eelgrass conservation in Kalmar County (see table 1 &2).

Consistent patterns include:

- **Strengths:** Stakeholders emphasized strong institutional support through protected eelgrass areas like the Rälla-Ekerum nature reserve, active cross-sectoral stakeholder engagement, and ongoing research collaborations with agencies such as SwAM and Linné University. Public engagement via media and environmental organizations also strengthens conservation efforts.

- **Weaknesses:** A recurring insight was the lack of active restoration compensation and limited local implementation of innovative eelgrass action plans. Stakeholders noted a passive approach to research, often following developments in other regions rather than leading local initiatives.

- **Opportunities:** Several innovative restoration techniques, including sand-capping and blue mussel projects, present promising avenues for future conservation. There is untapped potential in expanding public awareness campaigns and leveraging state funding schemes such as LOVA and LONA. Cross-border knowledge networks with Finland and Estonia also offer collaboration possibilities.

- **Threats:** Climate-related stressors, particularly warming temperatures and reduced salinity were consistently identified as significant threats that could negatively impact eelgrass populations.

Table 1 Swot themes and Evidence from Interview

Table below provides a detailed breakdown of the coded themes derived from the stakeholder interviews. Each theme is organized under the SWOT categories, highlighting specific factors influencing eelgrass conservation efforts as perceived by the stakeholders.

SWOT	**Theme**	**Evidence from Interview**
S	Protected eelgrass areas	Rälla-Ekerum nature reserve, application handling

S	Stakeholder engagement	Cross-sectoral involvement in marine improvement
S	Public engagement	Media, conferences, WWF articles
S	Research collaboration	Projects with SwAM & Linné University
S	Eelgrass in good condition	Monitoring shows widespread healthy meadows
W	No compensation restoration	Direct “No” to implementation
W	Lack of active research	Passive following of other regions
W	Limited implementation of action plan	No ongoing innovative trials locally
O	Innovative restoration techniques	Following sand-capping and blue mussel projects
O	Knowledge networks	Finnish and Estonian collaboration
O	Expand public awareness	No systemic campaigns mentioned
O	State funding schemes	LOVA, LONA as untapped eelgrass restoration resources
T	Climate stress	Warming + reduced salinity could harm Zostera

Table 2 Thematic Coding Table: Selected Interview Responses

This summary table consolidates the coded SWOT themes, offering a concise reference for the identified strengths, weaknesses, opportunities, and threats. It serves as a tool to inform strategic planning and decision-making in marine management practices.

Email Interview Question	Response Summary	Theme	SWOT Category
Current conservation actions	Protected areas, permit handling	Protective regulatory mechanisms	Strength
Coordination with SwAM	Collaboration on national restoration programs	Institutional collaboration	Strength

Reports and data availability	Shared eelgrass monitoring and global references	Data availability	Strength
Eutrophication management	Wetlands, mussel farming, sediment removal	Ecosystem-based mitigation	Opportunity / Threat
Compensation and restoration	No current implementation	Restoration gap	Weakness
Public awareness efforts	Media campaigns, conferences, WWF article	Public outreach	Strength / Opportunity
Research and innovation	Passive tracking of other regions' innovation	Innovation tracking	Opportunity / Weakness
Implementation challenges	Climate change, salinity impacts	Environmental vulnerability	Threat

4 Discussion

This chapter examines the spatial distribution of Zostera marina (eelgrass) in Kalmar Sund, focusing on key ecological factors such as light availability and nutrient levels influencing its presence. The findings highlight eelgrass as a vital indicator of coastal ecosystem health. A SWOT analysis evaluates the strengths, weaknesses, opportunities, and threats related to eelgrass conservation, aiming to inform effective marine management and promote sustainable efforts through interdisciplinary collaboration.

The following sections analyse these results, emphasizing eelgrass distribution as a measure of ecological health and its implications for coastal ecosystem management in Kalmar County. The discussion also integrates perspectives from marine ecology and environmental governance, offering practical recommendations for sustainable conservation initiatives.

4.1 Contrasting Drivers of Eelgrass Coverage: Evidence from Köpingsvik and Stora Rör

This study investigated how key ecological variables influence the spatial distribution of *Zostera marina* in two Kalmar Sund sites—Köpingsvik and Stora Rör—with contrasting outcomes.

In Köpingsvik, eelgrass coverage was closely linked to water quality. Greater Secchi depth (clearer water) corresponded with higher eelgrass presence, emphasizing the critical role of light availability. Elevated dissolved inorganic nitrogen (DIN) levels were associated with reduced eelgrass, likely due to nutrient-driven stressors such as algal blooms. Although chlorophyll-a showed a similar downward trend, its relationship with eelgrass was less clear. These results highlight the importance of nutrient reduction and water quality management for sustaining healthy seagrass meadows in Köpingsvik.

In contrast, Stora Rör showed no significant correlations between eelgrass coverage and the measured environmental factors, suggesting other influences—such as anthropogenic pressures (boating, shoreline changes), sediment type, wave exposure, or species interactions—may be more important. Eriander et al. (2016) note that coastal development and recreational boating can physically damage eelgrass and increase turbidity even without nutrient stress, potentially explaining the lack of clear patterns at this site.

The differing results between Köpingsvik and Stora Rör highlight the importance of site-specific conditions in eelgrass dynamics (Boström et al., 2014; Gustafsson & Boström, 2013). While Köpingsvik reflects clear nutrient and light effects (Waycott et al., 2009), Stora Rör's patterns suggest more complex local drivers, underscoring the need for longer-term or finer-scale monitoring.

These findings emphasize the necessity of localized, context-aware data to guide marine management in Kalmar County (Perry et al., 2020) and mirror broader concerns for seagrass ecosystems across the Baltic Sea and temperate regions facing nutrient stress, reduced water clarity, and habitat disturbance (Boström, 2014; Carstensen et al., 2013). Recognizing such spatial variability is vital for effective regional conservation strategies.

4.2 Key Environmental Drivers Shaping Eelgrass Depth in Kalmar Sund

The depth distribution of Zostera marina in Kalmar Sund reflects site-specific ecological factors, mainly light availability and nutrient levels, with depth largely governed by water clarity and nutrient dynamics.

At Stora Rör, there was a clear positive relationship between water clarity (Secchi depth) and eelgrass depth, indicating that better light penetration supports deeper eelgrass growth, consistent with established ecological understanding. Although dissolved inorganic phosphorus (DIP) showed a weak positive trend, it was not a strong limiting factor here, likely due to the general phosphorus limitation characteristic of the Baltic Sea. These findings emphasize the importance of maintaining water clarity to support eelgrass meadows, highlighting light as the primary driver of depth distribution at this site.

In contrast, Köpingsvik exhibited a significant negative relationship between dissolved inorganic nitrogen (DIN) and eelgrass depth, pointing to nutrient enrichment as a key stressor restricting eelgrass growth to shallower depths. This aligns with broader research demonstrating how nitrogen-driven eutrophication reduces light availability through increased phytoplankton blooms and epiphytic growth, ultimately limiting eelgrass colonization depth (Krause-Jensen et al., 2002). Despite including water clarity and chlorophyll-a in analyses, neither showed strong effects, possibly due to non-linear or threshold responses where nutrient enrichment has already degraded water quality beyond critical points (Dou et al., 2019). Furthermore, chlorophyll-a may not fully capture turbidity sources, as suspended sediments and colored dissolved organic matter also reduce light penetration (Boyer et al., 2009; Xu et al., 2016).

Overall, these site-specific differences highlight the nuanced roles of light and nutrients in shaping eelgrass depth distribution and underscore the need for tailored management focusing on water quality improvement and nutrient reduction.

4.3 Species Shifts Highlight Ecological Degradation

At Stora Rör, a notable shift in submerged vegetation occurred from 2001 to 2023, with a decline in *Zostera marina* (eelgrass) and a rise in *Stuckenia pectinata* (pondweed). This inverse relationship suggests species replacement driven by worsening ecological conditions, such as declining water quality, nutrient enrichment, or sediment destabilization, which negatively affect the light-sensitive eelgrass (Boström et al., 2014; Duarte et al., 2008; Moksnes et al., 2008).

This shift signals reduced habitat quality, as eelgrass meadows provide greater biodiversity, sediment stabilization, and ecosystem services than pondweed (McCloskey & Unsworth, 2015; Moksnes et al., 2008). Research indicates that mixed plant communities may enhance eelgrass resilience (Gustafsson & Boström, 2013), yet monocultures can recover faster due to less competition, suggesting that the move toward pondweed-dominated systems could undermine ecosystem stability and recovery.

While *S. pectinata* can colonize eelgrass habitats (Törnqvist et al., 2019), its preference for soft sediments and sheltered areas limits its ability to fully replace eelgrass in more exposed environments, indicating functional differences between the species.

These changes emphasize the need to monitor species composition alongside total vegetation cover, as shifts toward disturbance-tolerant species like pondweed can signal early ecological decline. Effective management requires timely detection of such shifts for habitat restoration.

Overall, this study confirms that eelgrass distribution in Kalmar Sund is strongly shaped by ecological conditions that vary by site. Köpingsvik’s eelgrass presence aligns with favorable light and nutrient conditions, while at Stora Rör, nutrient stress and species competition appear to limit eelgrass growth. This spatial variability underscores the importance of site-specific assessments and integrated consideration of eutrophication, light limitation, and biotic interactions in conservation planning for Kalmar County and similar coastal systems.

4.4 Marine Management Implications

The ecological patterns uncovered in this study provide valuable direction for managing *Zostera marina* habitats in Kalmar County. By revealing how eelgrass responds to local environmental conditions, both in terms of spatial distribution and shifts in species composition, the findings advocate for more adaptive, site-specific management approaches.

One of the most consistent patterns particularly evident in Köpingsvik is the negative influence of nutrient enrichment on eelgrass health. The association between elevated nitrogen levels and reduced eelgrass coverage supports broader evidence connecting eutrophication to seagrass decline (Waycott et al., 2009). This reinforces the importance of reducing nutrient inputs from sources such as agricultural runoff and wastewater discharges. Improved nutrient management can enhance water clarity, reduce algal overgrowth, and support healthier, more extensive eelgrass meadows.

Light availability, reflected by water transparency, also emerged as a key factor, especially at Stora Rör. There, clearer waters were associated with deeper eelgrass distribution, confirming that water clarity is a critical habitat determinant. Regular monitoring of Secchi depth offers a low-cost and ecologically relevant tool for assessing habitat suitability, particularly in identifying areas at risk from turbidity and informing restoration priorities (Carstensen et al., 2013).

Beyond these abiotic stressors, changes in species composition surfaced as an important ecological signal. At Stora Rör, the increasing dominance of *Stuckenia pectinata* over eelgrass suggests a shift toward disturbance-tolerant vegetation. Such transitions may occur without an overall loss in plant cover, yet signal underlying habitat degradation (Orth et al., 2006). Recognizing these compositional shifts is vital, as they may precede broader functional declines. Management frameworks should therefore include species-level assessments to detect early ecological warnings and guide timely interventions.

Crucially, the drivers affecting eelgrass varied markedly between sites. While environmental parameters were closely aligned with eelgrass patterns in Köpingsvik, their explanatory power was limited in Stora Rör. This suggests that other pressures—such as physical disturbance, altered sediment regimes, or legacy impacts from human activity—may play a stronger role. These site-specific dynamics underscore that effective marine management must be flexible and locally attuned, rather than relying on uniform solutions (Perry et al., 2020).

Given these complexities, long-term monitoring becomes essential. Understanding ecological change—especially delayed responses or cumulative impacts—requires sustained data collection over time. For locations like Stora Rör, where standard indicators yield limited insights, investing in broader ecological surveillance may be key to detecting subtle but significant shifts.

These results contribute to the growing evidence base for ecosystem-based marine spatial planning. By integrating environmental monitoring with conservation goals, it aligns with Sweden's obligations under the Marine Strategy Framework Directive and international biodiversity commitments. A comprehensive strategy focused on nutrient reduction, clarity monitoring, species composition, and site-specific management can help safeguard eelgrass habitats in the Baltic Sea, maintaining their ecological functions and supporting coastal resilience.

4.5 SWOT results and discussion for Kalmar County

Understanding local eelgrass management is vital for Kalmar County and offers insights applicable across the Baltic Sea. As eutrophication and climate change intensify, areas with relatively healthy eelgrass beds can serve as models for adaptive, ecosystem-based strategies. Insights from interviews with county representatives and secondary data were synthesized into a SWOT analysis, outlining key strengths, weaknesses, opportunities, and threats. Notably, some factors overlap between categories and may shift over time as environmental and management contexts evolve.

.

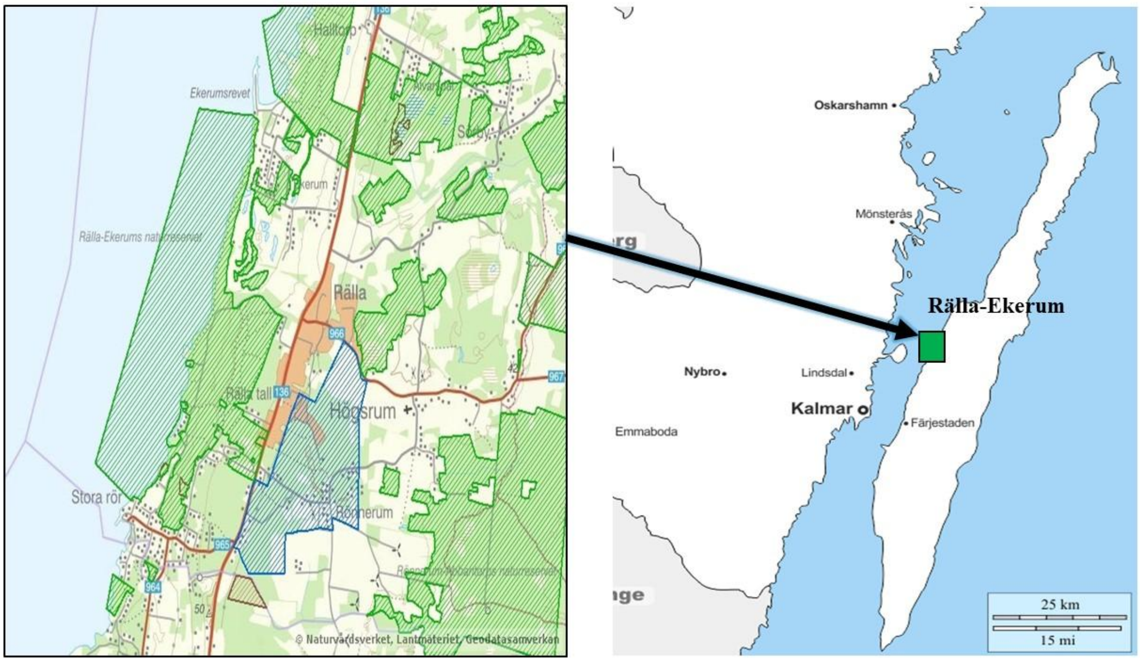
Table 3: Summary of categorized SWOT matrix results

Strengths	Weaknesses
1) Existing Protective Measures in Place 2) Multi-stakeholder Environmental Engagement 3) Participation in Public Awareness Initiatives 4)Collaboration with SwAM and Universities 5)Geographic and Ecological Advantage	1) Insufficient Local Restoration Activities 2) No Ongoing Local Restoration Research Projects 3) Gaps in Implementation of Action Plan
Opportunites	**Threats**
1) Potential to Adopt Innovative Techniques 2) Existing Knowledge & Regional Network for Learning 3)Untapped Potential for Public Awareness Expansion	1) Climate Change and Salinity Concerns 2) Eutrophication Pressure is Ongoing

4.5.1 Existing Protective Measures in Place

The Rälla-Ekerum Nature Reserve, located on the western coastline of Öland (see Fig. 20), is a cornerstone of Kalmar County's eelgrass conservation efforts. Spanning 603 hectares, including 352 hectares of marine habitats, the reserve aims to protect both terrestrial and marine biodiversity under the Swedish Environmental Code (Kalmar County Administrative Board, 2023).

Figure 20 Rälla-Ekerum Nature Reserve



The Rälla-Ekerum Nature Reserve is located along the western coastline of Öland in Kalmar County, situated just above Stora Rör. Area in the green is Nature reserve and one in blue is Water protection Area. The map is sourced from the Swedish Environmental Protection Agency's protected nature database (skyddadnatur.naturvardsverket.se*).*

A key strength of Kalmar County's eelgrass (*Zostera marina*) management is its formal protection within marine nature reserves, particularly the Rälla-Ekerum Nature Reserve. Located on Öland's west coast, this reserve spans 603 hectares—352 of which are marine—and is specifically designated to safeguard the shallow bay ecosystems that support extensive eelgrass beds (Kalmar County Administrative Board, 2023).

Under Swedish environmental law and the reserve's management plan, seabed-disturbing activities such as dredging, trawling, and the construction of harbors or piers are prohibited, supporting sediment stability and light availability—both critical for eelgrass health (SwAM, 2017). Motorboat speed limits and anchoring restrictions also help prevent vegetation uprooting.

"Eelgrass meadows are being included and protected in Rälla-Ekerum nature reserve... Considerations and measures for protecting eelgrass... are being addressed when the county

board handles applications for exploration in water”
(Jönsson, personal communication, November 8, 2024).

Beyond spatial protection, Kalmar County applies evidence-based permitting practices. Applications for activities like dock construction, cable-laying, or dredging are evaluated with eelgrass sensitivity in mind. This reflects the Swedish Eelgrass Action Plan, which recommends that permits for seabed interventions include environmental assessments accounting for eelgrass impact (SwAM, 2017).

The county also conducts long-term monitoring of eelgrass meadows inside and outside protected zones. These surveys yield important data on shoot density and meadow health, revealing both resilience and vulnerability across sites (Tobiasson, 2023).

4.5.2 Multi-Stakeholder Environmental Engagement

A significant strength of eelgrass conservation in Kalmar County is its cross-sector collaboration involving authorities, municipalities, industry groups, fishing organizations, and private landowners (Kalmar County Administrative Board, 2023). These partnerships enable coordinated responses and shared resources, which are vital for tackling the complex drivers of eelgrass decline.

Practical interventions include wetland construction and restoration to capture agricultural runoff, harvesting of excess marine biomass (e.g., filamentous algae), and pilot blue mussel cultivation to improve water clarity (Kalmar County Administrative Board, 2023; Kotta et al., 2020). Efforts to restore predatory fish populations like pike and perch also help reduce mesopredator abundance and control macroalgal overgrowth that can smother eelgrass beds (SwAM, 2017).

Many initiatives receive support through national funding programs such as LOVA (Local Water Conservation Projects) and LONA (Local Nature Conservation Initiatives), which promote stakeholder-led, sustainable action. Kalmar’s integrated approach reflects the principles of ecosystem-based management (EBM) endorsed by HELCOM and the EU’s Marine Strategy Framework Directive (MSFD), emphasizing multi-level governance for effective coastal conservation (HELCOM, 2015).

4.5.3 Participation in Public Awareness Initiatives

Kalmar County has played an active role in raising awareness about the ecological and socio-economic value of eelgrass ecosystems. During the SwAM-funded eelgrass restoration project (2016–2019), the County Administration Board collaborated with media and academic partners to promote eelgrass conservation. Coverage included interviews on Radio P4 Kalmar, local newspaper articles, and a documentary-style YouTube video that showcased eelgrass as vital nursery habitat for biodiversity and fisheries (P4 Kalmar, 2021; P4 Kalmar, 2016; YouTube, 2018).

County officials also shared project outcomes at national marine restoration conferences in 2018 and 2020 and were featured in WWF Sweden's *Eko* magazine, which targets environmentally engaged audiences. These efforts support Goal 3 of the Swedish Eelgrass Action Plan, which emphasizes public awareness of eelgrass as essential "blue infrastructure" (Tobiasson, 2023; Jönsson, personal communication).

By combining storytelling, media outreach, and educational tools, Kalmar has helped connect science and policy with the general public. This engagement promotes acceptance of conservation measures—such as anchoring restrictions or permitting regulations—and fosters long-term behavioral change in coastal communities.

4.5.4 Collaboration with SwAM and Universities

Kalmar County's collaboration with the Swedish Agency for Marine and Water Management (SwAM) and Linné University is a notable strength. Between 2016 and 2019, the county implemented an eelgrass restoration project using transplantation methods adapted from the Swedish west coast, testing their applicability in the Baltic Sea—a key example of applying scientific research to practical management.

SwAM's national "ÅGP" (Action Programme for Threatened Species and Habitats), which includes eelgrass, provides counties like Kalmar with technical guidance, funding, and standardized monitoring frameworks. This integration supports consistency across administrative levels and aligns local efforts with national and EU conservation objectives (SwAM, 2017).

Linné University in Kalmar has contributed as a research partner in seagrass ecology, helping to develop restoration strategies suited to the region. While no current projects are active, these established academic-government partnerships lay a strong foundation for future collaborative initiatives and funding opportunities through EU programs such as LIFE and Horizon Europe (European Commission, 2022).

4.5.5 Geographic and Ecological Advantage

Kalmar County benefits from a favorable geomorphological setting characterized by extensive shallow sandy bays with good light penetration—optimal conditions for eelgrass growth and persistence (Tobiasson, 2023). Monitoring data indicate that eelgrass meadows here are relatively stable and widely distributed compared to more degraded Baltic Sea areas, with sites like Bröttorpsören showing increasing shoot densities over time.

This ecological baseline allows the county to prioritize proactive management and early-warning monitoring rather than large-scale restoration, offering a more cost-effective and ecologically sound approach.

Moreover, extensive eelgrass coverage provides critical ecosystem services—including shoreline protection, fish nursery habitat, and carbon sequestration—that strengthen arguments for protective zoning and funding prioritization (Moksnes et al., 2016; Boström et al., 2014). Consequently, Kalmar serves as a potential stronghold or climate refuge for eelgrass, with important conservation implications for the Baltic region.

4.5.6 No Compensatory Restoration Projects Implemented

Although the importance of compensating for eelgrass habitat loss is acknowledged, Kalmar County has not yet implemented any formal compensatory restoration projects tied to permitted development (R. Jönsson, personal communication, November 8, 2024). The 2016–2019 SwAM-funded pilot focused on transplantation techniques but was conducted as an experimental effort rather than a requirement under the permitting process.

This represents a critical gap, as the Swedish Eelgrass Action Plan (SwAM, 2017) explicitly recommends compensatory restoration when meadows are damaged by activities like dredging or marina construction. However, in the absence of a national legal framework mandating marine habitat compensation—unlike in terrestrial systems—this guidance remains largely aspirational.

With ongoing coastal development, the lack of enforceable compensatory mechanisms increases the risk of net habitat loss. This could undermine Sweden’s commitments under the EU Marine Strategy Framework Directive (MSFD) and Biodiversity Strategy, and more broadly, Baltic Sea nations may fall short of EU biodiversity and climate resilience targets without scalable, legally supported restoration frameworks (Moksnes et al., 2021; SwAM, 2017).

4.5.7 Insufficient Local Restoration Activities

While Kalmar County has previously participated in restoration-related research, there are currently no ongoing field-based projects testing eelgrass restoration techniques or habitat engineering methods. According to local authorities, “we follow developments on the west coast and maintain some contact with research initiatives in Finland and Estonia, but we have not initiated any local trials yet” (R. Jönsson, personal communication, November 8, 2024).

These external collaborations offer useful insights, but the absence of locally adapted trials limits the county’s ability to address region-specific challenges—such as turbidity from bottom-driving macroalgae and sediment resuspension. Restoration ecology is highly site-dependent, and methods effective in high-salinity, high-energy environments like Sweden’s west coast may not be suitable for the brackish, sediment-rich conditions of the Baltic Sea.

Additionally, recent innovations—such as sand-capping, biofilm stabilization, and integrated eelgrass–mussel reef systems—have not yet been tested in Kalmar’s waters (HELCOM, 2021; Infantes et al., 2022). Without a formalized local research program, the county’s capacity to trial context-specific solutions and compete for funding requiring demonstration of innovative, evidence-based approaches is significantly reduced.

4.5.8 Gaps in Implementation of Action Plan Goals

Although Kalmar County aligns with several goals of Sweden’s national eelgrass action plan, key measures remain unimplemented or only partially addressed. According to R. Jönsson (personal communication, November 8, 2024), these include comprehensive mapping of eelgrass ecosystem services, formal integration into marine spatial planning, and the upscaling of compensatory restoration efforts.

Structural fragmentation contributes to these gaps, as responsibilities for marine spatial planning are split across national agencies, municipalities, and county boards, often causing delays. Limited staff capacity and regional funding further constrain long-term implementation. Kalmar’s past reliance on project-based funding from SwAM illustrates the challenge of sustaining efforts without stable financial support (SwAM, 2021).

As Sweden prepares for reporting under the forthcoming EU Nature Restoration Law—likely to include targets for seagrass recovery—these shortcomings may become more prominent unless addressed through improved institutional coordination and dedicated resources (Moksnes et al., 2016).

4.5.9 Potential to Adopt Innovative Techniques

Kalmar County is well-positioned to pilot next-generation restoration techniques proven effective in similar Baltic or semi-enclosed settings. For instance, sand-capping, which reduces sediment resuspension and enhances light conditions, has shown success in southern Sweden (Infantes et al., 2022).

Co-restoration approaches that combine eelgrass (Zostera marina) with bivalve habitats—such as blue mussel beds or oyster reefs—offer additional ecological benefits. Filter-feeding bivalves improve water clarity by removing suspended particles, thereby increasing light availability for eelgrass photosynthesis (Donaher et al., 2021). The physical structure of oyster reefs can also reduce erosion and facilitate eelgrass colonization (Grabowski & Peterson, 2007). These methods not only enhance seagrass survival but also boost macrofaunal diversity compared to single-species restoration (Boström et al., 2021; Fariñas-Franco et al., 2018).

Given its relatively healthy eelgrass baseline and prior transplantation experience, Kalmar could serve as a low-risk testbed for such innovations. Collaboration with regional universities (e.g., Linné and Gothenburg) and participation in EU research networks would support the co-design of methods tailored to local conditions (Moksnes et al., 2016).

These efforts align with HELCOM’s Baltic Sea Action Plan (2021–2030), which promotes innovation and adaptive management. Positioning Kalmar as a hub for ecological engineering could also attract external funding and research collaboration (HELCOM, 2021).

4.5.10 Existing Knowledge and Regional Network for Learning

Kalmar has established a strong foundation of knowledge and partnerships via earlier collaborations with SwAM and Linné University. Existing eelgrass monitoring programs, SwAM databases, and connections with researchers in Finland and Estonia provide an enabling environment for regional knowledge exchange (Jönsson, personal communication, November 8, 2024).

Public science communication efforts—such as radio interviews, film, and media articles—have built local awareness that can be leveraged for future citizen science, stakeholder engagement, and participatory restoration initiatives.

Additionally, Sweden’s national roadmap for a blue economy highlights marine habitat restoration as a strategic priority, offering potential for enhanced institutional support and alignment (SwAM, 2021).

4.5.11 Untapped Potential for Public Awareness Expansion

The Intergovernmental Oceanographic Commission (IOC) of UNESCO highlights the importance of enhancing ocean literacy as a foundation for sustainable ocean resource management. The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) offers a strategic framework to boost public engagement with marine issues, including the conservation of vital ecosystems like eelgrass meadows.

Educational programs, community involvement, and targeted outreach are central to this mission, aiming to translate scientific knowledge into community-level stewardship. Kalmar County could build on these principles by developing structured education and training efforts through coastal schools, tourism operators, or fishing associations, embedding eelgrass conservation more deeply into local cultural practices.

These strategies align with the Ocean Decade’s goals of fostering ocean literacy and expanding public participation in marine conservation (Intergovernmental Oceanographic Commission of UNESCO, 2021).

4.5.12 Climate Change and Salinity Concerns

Rising sea temperatures threaten the physiological stability of *Zostera marina*, promoting the growth of epiphytic algae that overshadow eelgrass leaves, reduce photosynthesis, and degrade habitat quality (Perry et al., 2020). Elevated temperatures may also shift species distributions and disrupt reproductive cycles, further weakening eelgrass populations (Xu et al., 2016).

In the Baltic Sea, already characterized by low salinity, projected declines due to increased precipitation and reduced saline inflows compound these challenges. Lower salinity limits eelgrass growth and resilience, making meadows more vulnerable to additional stressors. Moreover, climate-related changes such as sea-level rise and more frequent storms contribute to increased sedimentation and turbidity, reducing light availability critical for photosynthesis (Meier et al., 2022).

These interconnected stressors highlight the vulnerability of seagrass ecosystems and the urgent need for adaptive management strategies to safeguard their ecological functions and services.

In Kalmar County, climate change is expected to significantly reshape the distribution of *Z. marina*. According to modelling study by Törnqvist et al. (2019), eelgrass may disappear entirely north of Öland under both moderate (RCP 4.5) and high (RCP 8.5) warming scenarios, putting areas like Stora Rör and Köpingsvik at the northern limit of viable habitat.

While Kalmar Sound is identified as a potential climate refugium, its future viability is scenario dependent. Under RCP 4.5, eelgrass beds may remain relatively strong; under RCP 8.5, they are projected to become fragmented and weak. This underscores the acute vulnerability of these transitional zones and their significance in climate-adaptive marine spatial planning.

The loss of *Z. marina* would not only threaten biodiversity but also diminish essential ecosystem services such as fish nursery habitat, shoreline protection, and water quality regulation (Boström et al., 2014). As such, Kalmar Sound and the Öland coast represent both ecological frontlines and strategic priorities for conservation under a changing climate.

4.5.13 Eutrophication Pressure is Ongoing

Despite decades of mitigation efforts, eutrophication remains a persistent and complex environmental challenge in the Baltic Sea, including Kalmar County. Agricultural runoff, urban wastewater, and atmospheric nitrogen deposition continue to drive nutrient enrichment, resulting in algal blooms, hypoxia in benthic zones, and reduced light penetration—conditions detrimental to eelgrass ecosystems (Boström et al., 2014; Duarte et al., 2008). As noted by R. Jönsson (personal communication, November 8, 2024), "Although many stakeholders are working on it, it remains a key challenge... Yes, there is a lot of actions for many years, and ongoing."

Since the 1980s, efforts under frameworks such as the Baltic Sea Action Plan (BSAP) have sought to reduce nutrient inputs through improved agricultural practices, enhanced wastewater treatment, and stricter regulatory controls (HELCOM, 2021). While these interventions have contributed to measurable reductions in nitrogen and phosphorus loads, a eutrophication-free Baltic remains an elusive goal. Continued and coordinated actions are necessary to address ongoing pressures and legacy nutrient pools (HELCOM, 2023).

A particular challenge lies in the transboundary nature of nutrient loading, with variable contributions from surrounding nations. Sweden has made notable progress, but further reductions are still needed, especially regarding diffuse agricultural sources. In Kalmar County, targeted measures to limit agricultural runoff and optimize wastewater treatment remain essential. Additionally, opportunities exist to recover and reuse nutrient surpluses while mitigating the risk of further marine nutrient loss (McCrackin et al., 2018; HELCOM, 2021).

To enhance the effectiveness of these strategies, stronger alignment with national and EU-level policies, sustained funding, and long-term environmental monitoring are critical. The Swedish Agency for Marine and Water Management (SwAM, 2017) emphasizes that consistent monitoring and coordination across governance levels are prerequisites for achieving water quality improvements and restoring coastal habitats like eelgrass meadows.

5 Conclusions

This study reveals that eelgrass meadows in Kalmar Sound are shaped by a complex interplay of local environmental factors and broader ecological pressures. At Köpingsvik, water quality—particularly light availability and nutrient levels—strongly influences eelgrass presence, while at Stora Rör, additional local dynamics are at play, suggesting that eelgrass resilience is highly context-dependent. The observed encroachment of competing species highlights ongoing habitat shifts that require close monitoring.

Kalmar County benefits from a well-established framework for coastal habitat monitoring and stakeholder collaboration, yet gaps remain in fully implementing restoration actions and addressing pervasive threats such as nutrient enrichment and climate change. Innovations in restoration techniques and adaptive management strategies hold promise to improve eelgrass conservation outcomes.

Looking forward, the integration of locally tailored scientific knowledge, increased institutional coordination, and public engagement can strengthen eelgrass protection efforts. By prioritizing evidence-based management and fostering regional cooperation, Kalmar County has the potential to become a model for sustainable coastal ecosystem stewardship in the Baltic region.

6 References

Ahlgren, K. (2016, March 21). Ålgräs kan rädda Östersjön. SVT Nyheter. Retrieved December 9, 2024, from https://www.svt.se/nyheter/lokalt/smaland/algras-kan-radda-ostersjon

Baden, S. P., Gullström, M., Lundén, B., Pihl, L., & Rosenberg, R. (2003). Vanishing seagrass (Zostera marina, L.) in Swedish coastal waters. Ambio, 32(5), 374–377. https://doi.org/10.1579/0044-7447-32.5.374

Benson, J. L., Schlezinger, D., & Howes, B. L. (2013). Relationship between nitrogen concentration, light, and Zostera marina habitat quality and survival in southeastern Massachusetts estuaries. Journal of Environmental Management, 131, 129–137. https://doi.org/10.1016/j.jenvman.2013.09.003

Björk, M., Short, F., McLeod, E., & Beer, S. (2008). Managing seagrasses for resilience to climate change. IUCN. https://portals.iucn.org/library/efiles/documents/2008-019.pdf

Blindow, I., Hargeby, A., & Hilt, S. (2014). Facilitation of clear-water conditions in shallow lakes by macrophytes: Differences between charophyte and angiosperm dominance. Hydrobiologia, 737, 99–110. https://doi.org/10.1007/s10750-013-1687-2

Boström, C., Baden, S., Bockelmann, A. C., Dromph, K., Fredriksen, S., Gustafsson, C., ... & Rinde, E. (2014). Distribution, structure and function of Nordic eelgrass (Zostera marina) ecosystems: Implications for coastal management and conservation. Aquatic Conservation: Marine and Freshwater Ecosystems, 24(3), 410–434. https://doi.org/10.1002/aqc.2424

Boström, C., Pittman, S. J., Simenstad, C., & Kneib, R. T. (2021). Seagrass landscapes and their effects on associated fauna: A review. Marine Ecology Progress Series, 435, 287–302. https://doi.org/10.3354/meps09206

Bowker, N., & Tuffin, K. (2004). Email interviewing: Reflections on a qualitative research method. Journal of Research Practice, 1(1), Article M4. https://jrp.icaap.org/index.php/jrp/article/view/4/8

Boyer, J. N., Kelble, C. R., Ortner, P. B., & Rudnick, D. T. (2009). Phytoplankton bloom status: Chlorophyll a biomass as an indicator of water quality condition in the southern estuaries of Florida, USA. Ecological Indicators, 9(6), S56–S67.

Burns, S. (2010). The use of email interviews in qualitative research. Research in Nursing & Health, 33(5), 452–456. https://doi.org/10.1002/nur.20384

Carstensen, J., Krause-Jensen, D., Markager, S., Timmermann, K., & Windolf, J. (2013). Water clarity and eelgrass responses to nitrogen reductions in the eutrophic Skive Fjord, Denmark. Hydrobiologia, 704, 293–309.

Carstensen, J., Sánchez-Camacho, M., Duarte, C. M., Krause-Jensen, D., & Marbà, N. (2011). Connecting the dots: Responses of coastal ecosystems to changing nutrient concentrations.

Environmental Science & Technology, 45(21), 9122–9132. https://doi.org/10.1021/es202351y

Corbin, J., & Morse, J. M. (2003). The unstructured interactive interview: Issues of reciprocity and risks when dealing with sensitive topics. Qualitative Inquiry, 9(3), 335–354. https://doi.org/10.1177/1077800403009003001

Devlin, M., & Brodie, J. (2023). Nutrients and eutrophication. In A. Reichelt-Brushett (Ed.), Marine Pollution – Monitoring, Management and Mitigation (Springer Textbooks in Earth Sciences, Geography and Environment). Springer, Cham. https://doi.org/10.1007/978-3-031-10127-4_4

Donaher, S. E., Baillie, C. J., Smith, C. S., Zhang, Y. S., Albright, A., Trackenberg, S. N., Wellman, E. H., Woodard, N., & Gittman, R. K. (2021). Bivalve facilitation mediates seagrass recovery from physical disturbance in a temperate estuary. Ecosphere, 12(11), e03804. https://doi.org/10.1002/ecs2.3804

Dou, M., Ma, X., Zhang, Y., Zhang, Y., & Shi, Y. (2019). Modeling the interaction of light and nutrients as factors driving lake eutrophication. Ecological Modelling, 400, 41–52. https://doi.org/10.1016/j.ecolmodel.2019.03.008

Duarte, C. M. (1991). Seagrass depth limits. Aquatic Botany, 40(4), 363–377. https://doi.org/10.1016/0304-3770(91)90081-F

Duarte, C. M., Borum, J., Short, F. T., & Walker, D. I. (2008). Seagrass ecosystems: Their global status and prospects. In Aquatic ecosystems: Trends and global prospects (pp. 281–294). Cambridge University Press. https://doi.org/10.1017/CBO9780511751790.025

Eberly, L. E. (2007). Multiple linear regression. In W. T. Ambrosius (Ed.), *Topics in biostatistics* (Methods in Molecular Biology™, Vol. 404). Humana Press. https://doi.org/10.1007/978-1-59745-530-5_9

Eklöf, J. S., de la Torre-Castro, M., Gullström, M., Uku, J., Muthiga, N., Lyimo, T., & Bandeira, S. O. (2012). Sea urchin overgrazing of seagrasses: A review of current knowledge on causes, consequences, and management. *Estuarine, Coastal and Shelf Science*, *111*, 1–13. https://doi.org/10.1016/j.ecss.2008.05.005

Eriander, L., Infantes, E., Olofsson, M., Olsen, J. L., & Moksnes, P. O. (2016). Assessing methods for restoration of eelgrass (*Zostera marina*) in a cold temperate region. *Journal of Experimental Marine Biology and Ecology*, *479*, 76–88. https://doi.org/10.1016/j.jembe.2016.02.008

European Commission. (2022). *LIFE and Horizon Europe: Funding opportunities for environment and climate action.* https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/home

Fariñas-Franco, J. M., Pearce, B., Mazik, K., & Roberts, D. (2018). Co-restoration of mussel beds and seagrass meadows: Complementary benefits for biodiversity and ecosystem services. *Diversity*, *10*(6), 246. https://doi.org/10.3390/d10060246

Feld, C. K., Sousa, J. P., Silva, P. M., Dawson, T. P., & Martins da Silva, P. (2010). Indicators for biodiversity and ecosystem services: Towards an improved framework for ecosystems assessment. *Biodiversity and Conservation*, *19*(10), 2895–2919. https://doi.org/10.1007/s10531-010-9875-0

Grabowski, J. H., & Peterson, C. H. (2007). Restoring oyster reefs to recover ecosystem services. In K. Cuddington, J. E. Byers, W. G. Wilson, & A. Hastings (Eds.), *Ecosystem engineers: Concepts, theory and applications* (pp. 281–298). Elsevier.

Grech, A., Coles, R., & Marsh, H. (2011). A broad-scale assessment of the risk to coastal seagrasses from cumulative threats. *Marine Policy, 35*(5), 560–567. https://doi.org/10.1016/j.marpol.2011.03.003

Gustafsson, C., & Boström, C. (2013). Influence of neighboring plants on shading stress resistance and recovery of eelgrass, *Zostera marina* L. *PLoS ONE, 8*(5), e64064. https://doi.org/10.1371/journal.pone.0064064

Havs- och vattenmyndigheten. (2017, August 31). *Åtgärdsprogram för ålgräsängar* (J. Granit, Ed.). Havs- och vattenmyndigheten. ISBN 978-91-87967-72-6.

HELCOM. (2015). *Guideline for the implementation of ecosystem-based approach in maritime spatial planning (MSP) in the Baltic Sea area*. Baltic Marine Environment Protection Commission – HELCOM. https://helcom.fi/wp-content/uploads/2019/08/Guideline-for-the-implementation-of-ecosystem-based-approach-in-MSP-in-the-Baltic-Sea-area_June-2016.pdf

HELCOM. (2021). *HELCOM Baltic Sea Action Plan – 2021 update*. Helsinki Commission. https://helcom.fi/wp-content/uploads/2021/10/Baltic-Sea-Action-Plan-2021-update.pdf

Hemminga, M. A., & Duarte, C. M. (2000). *Seagrass ecology*. Cambridge University Press. https://doi.org/10.1017/CBO9780511525551

Helms, M. M., & Nixon, J. (2010). Exploring SWOT analysis – Where are we now? A review of academic research from the last decade. *Journal of Strategy and Management, 3*(3), 215–251. https://doi.org/10.1108/17554251011064837

Infantes, E., Crouzy, C., & Moksnes, P. O. (2016). Seed predation by the shore crab *Carcinus maenas*: A positive feedback preventing eelgrass recovery? *PLOS ONE, 11*(12), e0168128. https://doi.org/10.1371/journal.pone.0168128

Infantes, E., Pihl, L., Stål, J., & Moksnes, P.-O. (2022). Sand-capping as a method to improve light conditions and support seagrass restoration in turbid environments. *Marine Pollution Bulletin, 176*, 113456. https://doi.org/10.1016/j.marpolbul.2022.113456

Intergovernmental Oceanographic Commission of UNESCO. (2021). *United Nations Decade of Ocean Science for Sustainable Development (2021–2030): Implementation Plan.* https://unesdoc.unesco.org/ark:/48223/pf0000377082

Jemielniak, D. (2020). Qualitative research methods in the digital age: Challenges and opportunities. *International Journal of Social Research Methodology, 23*(2), 201–212. https://doi.org/10.1080/13645579.2018.1481879

Kahlert, M., Eilola, K., Mack, L., Meissner, K., Sandin, L., Strömberg, H., Uusitalo, L., Viktorsson, L., & Liess, A. (2020). Gaps in current Baltic Sea environmental monitoring – Science versus management perspectives. *Marine Pollution Bulletin, 160*, 111669. https://doi.org/10.1016/j.marpolbul.2020.111669

Kalmar County Administrative Board. (2020). *Decision on the establishment of Rälla-Ekerum Nature Reserve (Diary No: 511-6395-16).* Retrieved December 9, 2024, from https://skyddadnatur.naturvardsverket.se

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F. R., ... & Virtanen, E. (2020). Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. *Science of the Total Environment, 709*, 136144. https://doi.org/10.1016/j.scitotenv.2019.136144

Krause-Jensen, D., Pedersen, M. F., & Jensen, C. (2003). Regulation of eelgrass (*Zostera marina*) cover along depth gradients in Danish coastal waters. *Estuaries*, *26*, 866–877. https://doi.org/10.1007/BF02803345

McCloskey, R. M., & Unsworth, R. K. F. (2015). Decreasing seagrass density negatively influences associated fauna. *PeerJ, 3*, e1053. https://doi.org/10.7717/peerj.1053

Meier, H. E. M., Kniebusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., Myrberg, K., Ahola, M. P., Bartosova, A., Bonsdorff, E., Börgel, F., Capell, R., Carlén, I., Carlund, T., Carstensen, J., Christensen, O. B., Dierschke, V., Frauen, C., Frederiksen, M., ... Zhang, W. (2022). Climate change in the Baltic Sea region: A summary. *Earth System Dynamics*, *13*(2), 457–593. https://doi.org/10.5194/esd-13-457-2022

Moksnes, P. O., Gipperth, L., Eriander, L., Laas, K., Cole, S., & Infantes, E. (2016). *Management and restoration of eelgrass in Sweden – Ecological, legal and economic background* (Report No. 2016:8, 150 pp. including appendices). Swedish Agency for Marine and Water Management. ISBN 978-91-87967-16-0.

Moksnes, P. O., Gipperth, L., Eriander, L., Laas, K., Cole, S., & Infantes, E. (2021). *Management and restoration of eelgrass in Sweden – Ecological, legal and economic background* (Report No. 2016:8, 150 pp. including appendices). Swedish Agency for Marine and Water Management. ISBN 978-91-87967-16-0.

Moksnes, P. O., Gullström, M., Tryman, K., & Baden, S. (2008). Trophic cascades in a temperate seagrass community. *Oikos*, *117*(5), 763–777. https://doi.org/10.1111/j.0030-1299.2008.16521.x

Moksnes, P.-O., Infantes, E., & Olofsson, M. (2020). Restoration of eelgrass (*Zostera marina*) in temperate regions. *Marine Ecology Progress Series*, *631*, 63–80.

Nejrup, L. B., & Pedersen, M. F. (2008). Effects of salinity and water temperature on the ecological performance of *Zostera marina*. *Aquatic Botany*, *88*(3), 239–246. https://doi.org/10.1016/j.aquabot.2007.10.006

Niu, S., Zhang, P., Liu, J., Guo, D., & Zhang, X. (2012). The effect of temperature on the survival, growth, photosynthesis, and respiration of young seedlings of eelgrass *Zostera marina* L. *Aquaculture, 350*, 98–108. https://doi.org/10.1016/j.aquabot.2007.10.006

Nyqvist, A., André, C., Gullström, M., Baden, S., & Åberg, P. (2009). Dynamics of seagrass meadows on the Swedish Skagerrak coast. *Estuarine, Coastal and Shelf Science, 84*(3), 409–418. https://doi.org/10.1016/j.ecss.2009.07.010

Opdenakker, R. (2006). Advantages and disadvantages of four interview techniques in qualitative research. *Forum: Qualitative Social Research, 7*(4), Art. 11. http://nbn-resolving.de/urn:nbn:de:0114-fqs0604118

Orth, R. J., Carruthers, T. J. B., Dennison, W. C., Duarte, C. M., Fourqurean, J. W., Heck, K. L., Hughes, A. R., & Williams, S. L. (2006). A global crisis for seagrass ecosystems. *Bioscience, 56*(12), 987–996.

P4 Kalmar. (2016, March 21). Tre miljoner för att rädda sjögräsängar. *Sveriges Radio*. Retrieved December 9, 2024, from https://sverigesradio.se/artikel/6394264

P4 Kalmar. (2021, September 24). Ålgräsängarna är havets barnkammare. *Sveriges Radio*. Retrieved December 9, 2024, from https://sverigesradio.se/artikel/algrasangarna-ar-havets-barnkammare

Pell, B., McAdams, D. P., & Fitzpatrick, S. (2020). Asynchronous email interviewing: Methodological reflections. *Qualitative Research Journal, 20*(3), 283–296. https://doi.org/10.1108/QRJ-03-2019-0035

Perry, D., Hammar, L., Linderholm, H. W., & Gullström, M. (2020). Spatial risk assessment of global change impacts on Swedish seagrass ecosystems. *PLOS ONE, 15*(1), e0225318. https://doi.org/10.1371/journal.pone.0225318

Raun, A. L., & Borum, J. (2013). Combined impact of water column oxygen and temperature on internal oxygen status and growth of *Zostera marina* seedlings and adult shoots. *Journal of Experimental Marine Biology and Ecology*, *441*, 16–22. https://doi.org/10.1016/j.jembe.2013.01.014

Ruxton, G. D. (2006). The unequal variance t-test is an underused alternative to Student's t-test and the Mann–Whitney U test. *Behavioral Ecology, 17*(4), 688–690. https://doi.org/10.1093/beheco/ark016

Santos, C., Scott, A., Arias-Ortiz, A., Jones, B. L., Kennedy, H., Mazarrasa, I., McKenzie, L. J., Nordlund, L. M., Torre-Castro, M., Unsworth, R. K. F., & Ambo-Rappe, R. (2021). Seagrass ecosystem services: Assessment and scale of benefits. *Ecosystem Services*, *48*, 101207. https://doi.org/10.1016/j.ecoser.2020.101207

Schober, P., Boer, C., & Schwarte, L. A. (2018). Correlation coefficients: Appropriate use and interpretation. *Anesthesia & Analgesia, 126*(5), 1763–1768. https://doi.org/10.1213/ANE.0000000000002864

Swedish Agency for Marine and Water Management (SwAM). (2017). *Action Plan for Eelgrass Meadows (2017–2021)*. Report 2017:24.

Swedish Agency for Marine and Water Management (SwAM). (2021). *Roadmap for a sustainable blue economy in Sweden*. https://www.havochvatten.se/en/publications/publikationer/2021-11-29-roadmap-for-a-sustainable-blue-economy-in-sweden.html

Swedish Environmental Protection Agency. (2015). *Guidelines for Biotope Protection for Eelgrass.*

Teixeira, H., Berg, T., Uusitalo, L., Fürhaupter, K., Heiskanen, A.-S., Mazik, K., ... & Borja, Á. (2016). A catalogue of marine biodiversity indicators. *Frontiers in Marine Science, 3*, 207. https://doi.org/10.3389/fmars.2016.00207

Tobiasson, H. (2023). *Ålgräs i Kalmar län: Övervakning och vegetationstrender 2023*. Linnéuniversitetet.

Törnqvist, O., Jonsson, P. R., & Hume, D. (2019). *Climate refugia in the Baltic Sea: Modelling future important habitats by using climate projections.* Pan Baltic Scope report, Uppsala & Gothenburg.

Unsworth, R. K. F., Nordlund, L. M., & Cullen-Unsworth, L. C. (2015). Seagrass meadows support global fisheries production. *Conservation Letters, 12*(5), 1–9. https://doi.org/10.1111/conl.12273

Waycott, M., Duarte, C. M., Carruthers, T. J., Orth, R. J., Dennison, W. C., Olyarnik, S., ... & Williams, S. L. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences, 106*(30), 12377–12381.

Xu, S., Zhou, Y., Wang, P., Wang, F., Zhang, X., & Gu, R. (2016). Salinity and temperature significantly influence seed germination, seedling establishment, and seedling growth of eelgrass *Zostera marina* L. *PeerJ, 4*, e2697. https://doi.org/10.7717/peerj.2697

YouTube. (2018). *En film om ålgräs – Sveriges mest undervärderade växt.* Retrieved December 9, 2024, from https://www.youtube.com/watch?v=1FJlDkhLrn4

Yu, L., Khachaturyan, M., Matschiner, M., et al. (2023). Ocean current patterns drive the worldwide colonization of eelgrass (*Zostera marina*). *Nature Plants, 9*, 1207–1220. https://doi.org/10.1038/s41477-023-01464-3

7 Appendix A: Questions Sent to Kalmar County Administrative Board

To support this research on eelgrass (Zostera marina) management in Kalmar County, I contacted the Kalmar County Administrative Board (Länsstyrelsen Kalmar län) on two occasions in 2024. Below is a list of the questions sent during these communications. Answers are excluded due to ethical and privacy considerations.

Email 1

Subject: Request for Information – Eelgrass Conservation in Kalmar County

1. **Current Conservation Actions:**
   Could you provide details on any current measures or strategies being implemented in Kalmar County to protect eelgrass meadows from eutrophication, physical disturbances, or other environmental stressors? I am especially interested in conservation efforts within Natura 2000 sites or other protected areas.
2. **Coordination with SwAM:**
   Are there any collaborations between Kalmar County and the Swedish Agency for Marine and Water Management (SwAM) focused on eelgrass and other related marine habitats?
3. **Access to Reports and Data:**
   If possible, could you direct me to any reports, research data, or resources concerning eelgrass distribution, health, or conservation within Kalmar County?

Email 2

Subject: Follow-up Questions – Eelgrass Action Plan Implementation

1. **Eutrophication Management:**
   Are there any specific strategies or measures being implemented to address nutrient inputs or improve water clarity in the region?
2. **Compensation and Restoration Efforts:**
   Has Kalmar County implemented any compensatory restoration projects for eelgrass loss due to permitted activities?
3. **Public Awareness and Training Initiatives:**
   Has the county undertaken any public awareness campaigns or training sessions related to the ecological importance and socio-economic value of eelgrass?
4. **Collaborative Research and Innovation:**
   Are there any ongoing or planned research initiatives in Kalmar County aimed at developing new restoration methods, such as controlling bottom-driving macroalgae or sediment resuspension?
5. **Challenges in Implementing the Action Plan:**
   What are the primary challenges in achieving the goals of the eelgrass action plan, particularly regarding eutrophication management and restoration?