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Original Research Paper

Investigating the Role of Seagrass and Saltmarsh Ecosystems as Climate-Resilient Refugia for Aquatic Wildlife

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Seagrass,
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Climate resilience,
Aquatic wildlife,
Refugia,
Conservation,
Ecosystem restoration

Abstract
Seagrass and saltmarsh ecosystems are another critical habitat of many aquatic organisms, where they play an essential role in providing refugia to enhance the resilience of marine biodiversity in the face of climate change. These ecosystems serve as natural buffers against coastal erosion, breeding grounds, and habitats for a variety of species, depending on the unique environmental conditions. The seagrass meadows and saltmarsh have been threatened by humans and other climate-related factors, such as rising sea levels and temperature variations, despite their importance. Past research indicates the importance of these ecosystems as climate refugia, providing refuge to species facing environmental pressure. The adaptive capacity of these ecosystems, including carbon sequestration, is said to be the reason they are resilient and can provide stable conditions for species, allowing them to move and survive. Case studies have shown how particular species, such as fish, invertebrates, and waterfowl, take advantage of these habitats during times of change. The paper discusses how seagrass and saltmarsh ecosystems help make aquatic wildlife more resilient, especially as climate refugia, and offers ideas for restoring and conserving them. The discoveries highlight the significance of these ecosystems for climate adaptation and recommend strengthening conservation and restoration efforts to preserve them and support biodiversity.

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Introduction

Seagrass and saltmarsh ecosystems play an important role in coastal landscapes, providing essential ecosystem services to marine and estuarine biodiversity (Graham et al., 2024; Vijayaraghavan, 2021). Seagrasses are submerged plants growing in shallow waters and coastal lands, whereas saltmarshes are coastal wetlands dominated by plants tolerant of salt (Manjunath et al., 2025; Doolan & Hynes, 2023). The two ecosystems play a vital role in supporting aquatic organisms by providing food, shelter, and breeding grounds (Arkema et al., 2024). These ecosystems act as nurseries for fish and invertebrates, supporting a wide variety of species throughout their life cycles. Moreover, they preserve coastal communities by stabilizing sediment, mitigating erosion, and buffering against storm surges, thereby enhancing coastal resilience (Kurian & Sultana, 2024). Previous literature has noted that seagrass and saltmarsh ecosystems are important refugia, providing a haven for species in unfavorable environmental conditions (Engelbrecht et al., 2025; Graham et al., 2025). These ecosystems are all the more critical as climate change accelerates, with rising sea levels, habitat loss, and extreme temperatures threatening species (Assegid & Ketema, 2023). It has been demonstrated that seagrass meadows and saltmarshes provide consistent shelter by offering microhabitats that shield species from environmental stress (Rajan & Ramya, 2024; Saavedra-Hortua et al., 2023; Henriksson et al., 2024).

An example is seagrasses, which reduce the impacts of ocean acidification and warming by stabilizing the seabed and providing carbon sequestration benefits (Azizova et al., 2025; Foster & Hughes, 2025). In contrast, saltmarshes do so through migratory birds and species that depend on stable water salinity. Research has also identified key factors in these ecosystems' resistance, including biodiversity, habitat complexity, and species' adaptation to environmental stress (Schoeman et al., 2023). Juvenile fish and migratory birds are among the species that benefit from the protection of such ecosystems, especially during extreme weather or climate change-driven alterations (Campos et al., 2024). Moreover, numerous case studies demonstrate the beneficial effects of these ecosystems on species populations, and they play an important role in preserving ecosystem services and supporting biodiversity (Eger, 2022).

To conclude, seagrass and saltmarsh ecosystems are crucial for enhancing the resilience of aquatic species and providing the refuge biodiversity needs amid climate change (Farthing, 2023). Their strength depends on several factors, and knowledge of these dynamics is key to successful conservation and management measures. In the subsequent sections, the methodologies to be employed to determine the role of these ecosystems as climate-resilient refugia for aquatic wildlife will be described (McCullough et al., 2024; Russo et al., 2025).

Key Contributions

- This paper emphasizes the role of seagrass and saltmarshes as essential habitats that support the survival of aquatic life under environmental stress, i.e., in response to adverse climatic conditions such as temperature-driven climate change and sea-level rise.

- The study identifies the main factors contributing to these ecosystems' resilience: their biodiversity, the complexity of their habitats, and their capacity to sequester carbon, all of which are necessary to sustain species.
- The paper provides practical information on the restoration and management of seagrass and saltmarsh ecosystems, with reference to their relevance to biodiversity management and climate adaptation strategies (Arvinth, 2025).

This paper examines how seagrass and saltmarsh ecosystems serve as climate-resilient refugia for aquatic wildlife and provides valuable insights into the ecological and conservation issues surrounding these ecosystems. Section II describes the selection of study sites, the field survey, remote sensing as a data-collection method, and advanced GIS and statistical analysis to measure ecosystem resilience. Section III shows the different levels of resilience of these ecosystems, the dependence of key species on them, and the health of the ecosystems in various locations. In section IV, the findings are attributed to conservation and management measures regarding the restoration potential and the need to further research the adaptive capacity of such habitats. Section V underscores the extreme relevance of these ecosystems for climate adaptation, biodiversity conservation, and ecosystem services, and calls for continued conservation efforts and research to ensure their long-term sustainability amid current environmental challenges.

Materials and Methods

This section presents the procedure for evaluating the role of seagrass and saltmarsh as climate-resilient refugia for aquatic wildlife. The overall design of the research entailed a scrupulous selection of research sites, a thorough data collection process based on field surveys and remote sensing, and sophisticated data analysis using GIS mapping and statistical methods.

Study Sites

The research locations were selected based on ecological importance and their ability to capture the environment's diversity. Coastal areas with existing seagrass meadows and saltmarshes of varying exposure to climate-related stressors (e.g., rising sea levels, temperature changes, and storm frequency) were selected as sites. These were both sites with preserved areas and sites with human activity, providing a chance to compare natural and disturbed ecosystems. The sites chosen provided a wide range of cross-sections of different habitats, which may provide some information on the resilience of these ecosystems to various environmental stresses.

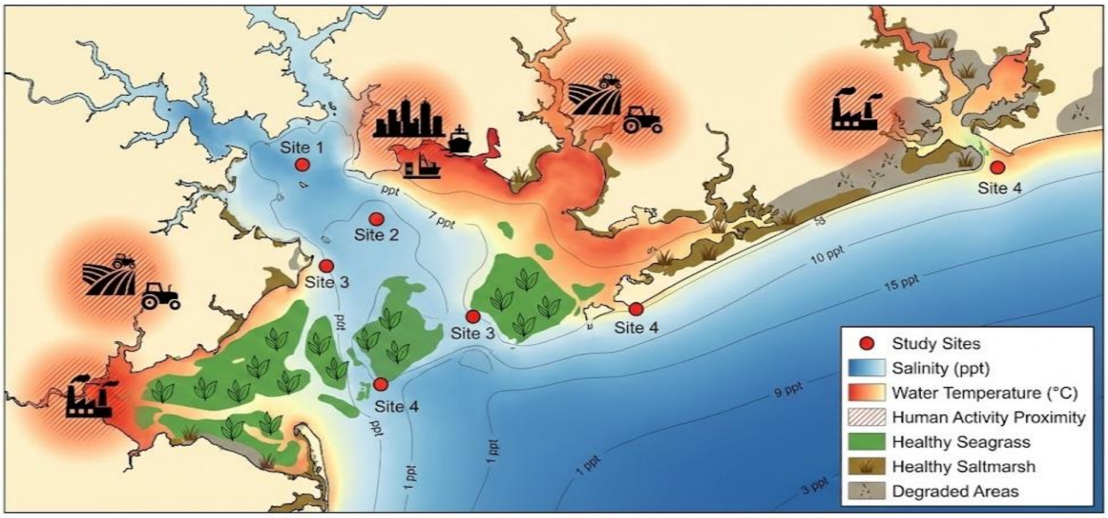

Figure 1: Map of Study Sites and Habitat Distribution

Figure 1 shows the geographic locations of the study sites along the coast, indicating the distribution of seagrass and salt marsh habitats. It has areas of color coding to show water salinity levels, the proximity of human activity, and habitat quality, to differentiate between healthy and unhealthy seagrass and salt marsh. Environmental conditions at the study sites are clearly depicted on the map and provide context for the various habitats and their susceptibility to climatic factors. It is one of the main instruments for understanding the spatial linkages between anthropogenic activity and ecosystem well-being.

Data Collection Methods

This research paper used a combination of remote sensing and field surveys as data collection tools. A field survey of the sites was conducted to determine the extent of seagrass and salt marsh habitats and their health. In these surveys, vegetation was sampled using standard methods, such as transect and quadrat sampling, to assess vegetation density, species composition, and biomass. Monitoring of environmental variables was conducted by measuring water temperature, salinity, pH, turbidity, and dissolved oxygen at different points within the habitats to assess the general health of the ecosystems. Remote sensing methods were used to obtain large-scale spatial data to complement field data. Seagrass and salt marsh habitats were mapped using satellite data and drone-based aerial surveys, and their sizes and conditions were compared in the past. These techniques provided information on changes in habitat cover over time and enabled us to analyze spatial patterns in environmental conditions and habitat fragmentation. Remote sensing was also used to monitor hard-to-reach regions on foot, thereby enabling more painstaking data collection in vast, remote areas.

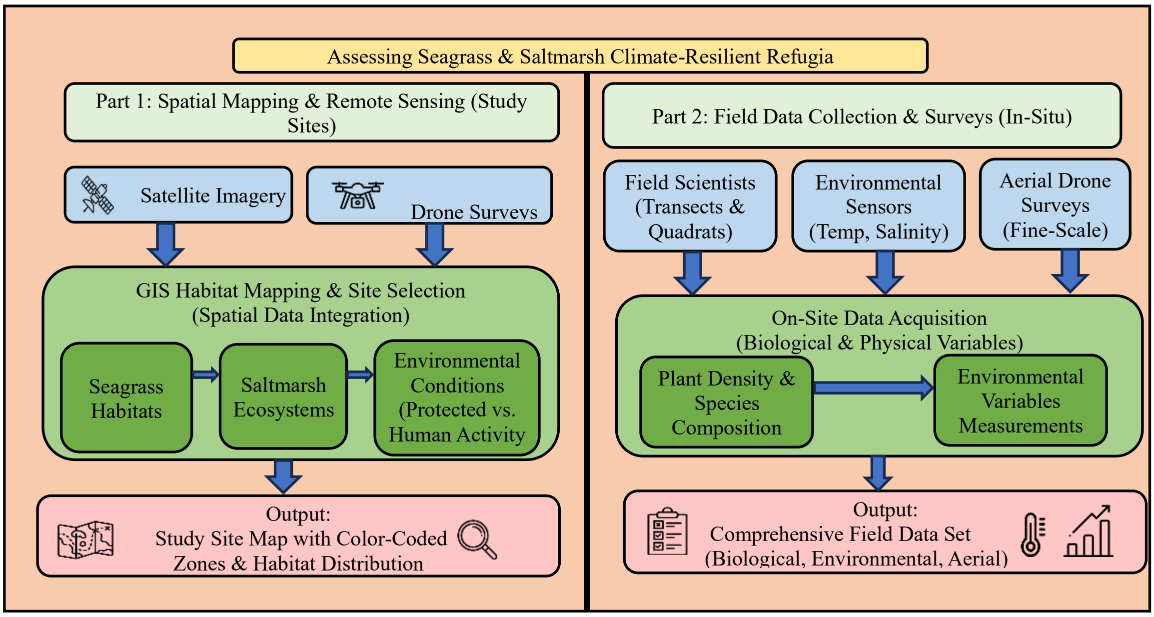

Figure 2: Spatial Mapping & Remote Sensing, Field Data Collection

Figure 2 summarizes the study methodology, divided into two sections: spatial mapping and remote sensing (Part 1) and field data collection and surveys (Part 2). Part 1 shows the use of satellite images with drone surveys and GIS of habitats to identify the study sites and track the distribution of habitats. Part 2 is on a data collection process in the field, in which field scientists perform transects and quadrat sampling, and the process of obtaining biological and environmental variables using sensors. The following diagram will illustrate the holistic method of gathering spatial, biological, and ecological data in order to evaluate the resilience of seagrass and salt marsh ecosystems.

Data Analysis Techniques

After the data were collected, the spatial distributions of habitat and ecosystem health data were analyzed by Geographic Information System (GIS) mapping. The GIS enabled the combination of the data collected in the field with the remote sensors to create detailed maps of the habitat area, environmental parameters, and distribution of species at the study sites. These maps were then applied to determine the association between the condition of habitats and their ecological contexts, including closeness to human development or vulnerability to the effects of climate change.

There were statistical tests to establish a correlation between habitat variables and species richness. Interactions between the environmental variables and ecosystem health were investigated using multivariate analysis, which comprised Principal Component Analysis (PCA). The possible effects of climate variables on the presence of species and the resilience of the ecosystem were also used in regression models. Using GIS mapping together with statistical models, the research was in a position to measure the strength of the seagrass and salt marsh ecosystems and determine the main factors leading to such resilience in the ecosystems to support wildlife in times of environmental stress.

Results

In this part, we will set out the findings of the data collection and analysis, which will include the resilience of seagrass and salt marsh ecosystems as climate refugia of aquatic wildlife. The findings are classified under three broad divisions, which are ecosystem health evaluation, species dependence on these environments, and comparison of ecosystem health in various locations of the study.

Ecosystem Health and Resilience

There were also a large number of variations in the overall health of the seagrass and salt marsh ecosystems at the study sites, and an apparent variation was found in the exposed habitats to human activity and the more preserved habitats. The personalities of sites with little anthropogenic activity were healthier in terms of seagrass meadows and saltmarsh, which were more densely vegetated, more diverse in species, and had better water quality. Conversely, regions where agricultural runoff, urbanization, and greater human impact occurred had lower habitat quality characterized by lower seagrass cover, decreased levels of plant diversity, and higher levels of pollutants. Drone and satellite imagery recorded notable time variations in the extent of habitat occurring to some extent with a gradual loss in the seagrass and saltmarsh cover, especially around regions of strong anthropogenic influence. GIS mapping established that habitats that were closer to urban centers or agricultural lands had more degraded and fragmented habitats, with salt marsh habitats in most cases being substituted by less resilient species or barren regions. The evidence showed that seagrass meadows, especially, had served as more resilient ecosystems than saltmarsh, probably because of their capacity to stabilize the sediments and offer continuous cover, which cushions against the changes in temperature and storm floods. Nonetheless, saltmarsh were also shown to have the ability to provide essential sanctuary to migratory animals, especially in the case of extreme weather patterns.

Species Dependence on Seagrass and Saltmarsh Ecosystems

The data of the species abundance at field surveys indicated that such vital species as juvenile Lutjanus campechanus (red snapper) and Penaeus vannamei (white shrimp) were very dependent on seagrass and salt marsh ecosystems in order to find shelter, food, and mates. The health of the habitat was positively associated with these species and was found to have higher populations of these species in habitats that had healthy seagrass meadows and saltmarsh. It was mainly the juvenile fish, such as Lutjanus campechanus, that required seagrass beds to offer protection against predators, with surveys showing that a high population of fish existed in those areas with high seagrass cover compared to those with sparse or degraded seagrass cover. The same was observed with Penaeus vannamei, which were readily abundant in the salt marsh habitats where they would seek shelter in the thick bushes and also feed on them. It was also discovered that migratory birds, including Charadrius melodus (piping plover), frequent the salt marsh areas and nest in the areas and forage. The well-being of salt marsh ecosystems played a significant role in sustaining these species, and an increase in the density of bird populations could be observed in places with preserved salt marsh vegetation.

Comparison of Ecosystem Health Across Sites

The analysis of the study sites in terms of ecosystem health showed that there were a number of interesting patterns. Those sites that were in agricultural proximity or urban developments had much lower habitat quality and had poor seagrass and salt marsh health. Such sites tended to have lower species diversity and lower abundance of some of the major wildlife species. On the other hand, more secure or remote and less disturbed sites had healthier environments with good water and biodiversity. Among the various discoveries was the significant effect of nutrient pollution by the agricultural runoff, especially in regions where the levels of nitrogen and phosphorus were higher. The death of seagrass meadows was linked to these pollutants since the nutrient-rich waters enabled the development of algae, which competed with seagrasses in terms of nutrients and light.

Table 1: Species Abundance in Healthy vs. Degraded Seagrass and Saltmarsh Habitats

Habitat Type	Lutjanus campechanus (Red Snapper) Abundance	Penaeus vannamei (White Shrimp) Abundance	Charadrius melodus (Piping Plover) Abundance
Healthy Seagrass	120 individuals/km²	50 individuals/km²	10 individuals/km²
Degraded Seagrass	45 individuals/km²	25 individuals/km²	5 individuals/km²
Healthy Saltmarsh	40 individuals/km²	180 individuals/km²	35 individuals/km²
Degraded Saltmarsh	15 individuals/km²	60 individuals/km²	10 individuals/km²

Moreover, the increase in salinity in zones focused on saltwater intrusion as a result of sea-level rise was associated with stress in the ecosystems of saltmarsh that resulted in poor plant health and habitat availability of migrating species.

Table 1 is a summary of the abundance of the critical species in the healthy and degraded seagrass and salt marsh habitats. As indicated, there were more juvenile fish and invertebrates in healthy habitats as opposed to degraded areas, which had fewer species.

Table 2: Water Quality and Habitat Health Across Study Sites

Site	Salinity (ppt)	Temperature (°C)	pH	Turbidity (NTU)	Habitat Health (Scale 1-5)
Site 1 (Protected)	32	27.4	8.1	2.1	5
Site 2 (Disturbed)	34	28.3	7.9	8.4	3
Site 3 (Urban)	35	29.2	7.5	15.2	2
Site 4 (Agricultural)	36	30.0	7.3	20.5	1

Table 2 is a comparison of water quality and habitat health in the study sites. The disturbed and urban sites had higher turbidity and lower PH, which was associated with worse habitat health, which shows that human activities have an adverse effect on the water quality and the conditions of ecosystems.

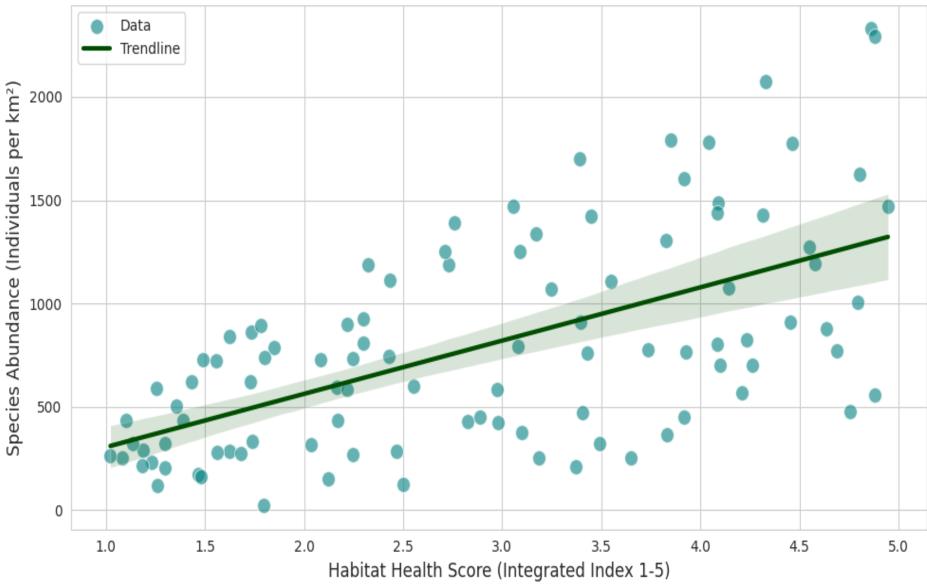

Figure 3: Relationship Between Habitat Health and Species Abundance in Seagrass and Saltmarsh Ecosystems

Figure 3 presents the correlation between the health of the habitat (measured on a scale of 1 to 5) and the quantity of species (number of individuals per km2) in seagrass and salt marsh environments. The X-axis is the health score of the habitat, where 1 corresponds to degraded habitats and 5 corresponds to pristine ecosystems. The abundance of the species is depicted on the Y-axis, and this is used to indicate the number of people of important species (e.g., juvenile fish and invertebrates) per square kilometer in the habitats. The scatter plot presents the data obtained at different study locations, and there is a positive correlation between healthy habitats and a high number of species. The abundance of the species is much greater with the improvement of the state of the habitat (high score), which proves that pristine ecosystems are better able to support the abundance and great diversity of aquatic wildlife. This positive correlation is modeled by the trendline (black line), and the shaded region is the 95% confidence interval, which means that the data would fall within the range in which we are sure to get the true trend. This graph highlights the need to conserve and rehabilitate healthy seagrass and salt marsh ecosystems, as these ecosystems offer essential refugia to aquatic life, particularly following environmental stressors such as climate change.

Discussion

Seagrass and salt marsh ecosystems are essential in supporting biodiversity as they offer shelter to the young fish, shrimp, and migratory birds. We find that the quality of the habitat directly correlates with the abundance of a species and that healthy ecosystems have a higher population. On the other hand, habitats that have been degraded (most of the time as a result of pollution and human activity) experience a rapid reduction in the number of species. The stability of these ecosystems is highly dependent on the quality of water, nutrients, and human activities.

The adverse effect of human activity, such as urbanization, agricultural runoff, and pollution, has a considerable adverse impact on both the seagrass and the salt marsh ecosystems. Also, stressors that occur because of climate change, e.g., higher sea levels and more storm events, also contribute to habitat degradation. All these pressures have underscored the importance of planning conservation initiatives that will help deal with local as well as global environmental issues. In order to counter these threats, it is necessary to have effective management strategies. The most important solutions are the creation of marine protected areas (MPAs), establishing coastal buffer zones, and providing restoration initiatives, including the replantation of indigenous plants and improving water quality. Moreover, the ecosystems will be able to adjust to climate change because of adaptive management strategies, which will be supported by constant monitoring and research. The other important aspect of long-term sustainability of conserving the seagrass and salt marsh ecosystems is to involve local communities in conservation activities so that these ecosystems can remain active.

Conclusion

This paper emphasizes how essential seagrass and salt marsh ecosystems are in supporting biodiversity and forming climate-resilient refugia for aquatic organisms. The greater abundance of species occurs in healthy ecosystems (high plant density with low disturbances), and there is a vast amount of species loss in degraded habitats. We have shown the synergy between the dangers of climate change and human action that are increasing the rate of habitat destruction. In order to mitigate such effects, it is essential to keep up conservation plans like marine protected areas (MPAs), coastal buffer zones, and to ensure that the water quality is improved. The processes of restoring the habitats by planting native vegetation and minimizing nutrient pollution will be crucial in the restoration of these habitats. The next topic of research must be on long-term tracking to determine the ability of such ecosystems to adapt to climate change, particularly the reactions of the species to changes in temperature, salinity, and storm frequency. Also, the development of restoration methods and the incorporation of community-level conservation and policy will all guarantee the sustainability of seagrass and saltmarsh, and ultimately protect the biodiversity and improve the vulnerability of the coastal ecosystems to the increasing environmental pressure.

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