



Original Research Paper

Climate-Induced Phenological Shifts and the Disruption of Species Interactions in Baltic Sea Ecosystem

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Key Words	Abstract
Climate change, Phenological shifts, Baltic sea, Species interactions, Trophic mismatch, plankton blooms, Fish spawning, Ecosystem disruption, Food web dynamics, Biodiversity, Ecosystem management.	Phenological changes in the Baltic Sea ecosystem as a result of climate influence the timing of biological processes, including fish spawning, bird migration, and plankton bloom, causing major changes in species interactions. Such changes are mainly triggered by the increase in sea temperatures, salinity changes and variations in ice cover that impact the primary producers and consumers within the food web. A good example here is the non-correlation between the earlier plankton proliferation and the preprogrammed reproductive periods in fish, especially herring. This trophic imbalance affects the food supply of higher trophic levels such as fish larvae, seabirds and marine mammals which result in low survival rates and reproductive success. These disruptive interactions can be seen through changes in predator-prey interactions, species composition, and overall ecosystem instability. To determine the different climate factor, salinity change to increasing the sea temperature by 1.2, Change the ice cover by 1.4, previous plankton blooms by 1.45 and Altered salinity by 1.5. In this paper, the author discusses the cause and effects of the phenological changes in the Baltic Sea due to climate change and the necessity to implement adaptive management approaches to handle the current ecological crisis.

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Introduction

Basternic sea ecosystem contains a rich variety of species including planktons, marine mammals among other species and they are important in food web and ecosystem (Viitasalo & Bonsdorff, 2022; Forsblom et al., 2024). Nevertheless, the ecosystem is being affected by climate change, which results in the increase of sea temperatures, salinity change, and the shift of ice cover affecting the timing of important biological phenomena such as the plankton blooms and fish spawning (Pöysä, 2023). These alterations bring about trophic mismatches, which create balance instability among species and the food web. By incorporating forest ecology and climate resilience into management framework, sustainability can be promoted through the interconnection between marine and terrestrial systems so that the two ecosystems can adjust to the changing climate and balance the biodiversity (Geetha, 2024). Over the last several decades, the area has been witnessing an increase in sea temperatures, changes in salinity distribution, and changes in ice cover, which have significant implications on the timing of biological processes. This is referred to as phenological shifts (Arula et al., 2014). The science of timing the biological processes concerning the changes in the environment has turned out to be an important field of research in terms of climate change. Moreover, stress and disease process induced by climate in aquaculture species are also becoming a major issue (Matkarimov et al., 2025).

Phenological change in marine ecosystems can be observed as the changing time of

spawning, migration or blooming among other life-cycle events, which can destabilize the interactions between species (Reckermann et al., 2022; Harvey et al., 2003). The manifestations of these disturbances have been witnessed in the Baltic Sea, where there were previous plankton boom, inappropriate spawning time of fish, and migration changes of seabirds and marine mammals. The impacts of such changes are very vast not just to specific species but also to the operation of the whole ecosystem. The change in interactions of species, especially predator and prey, has resulted in a trophic mismatch, that is species that have soared earlier than the predators can adjust to the novel timing. The marine food web is based on phytoplankton and zooplankton, which serve as the important food sources of the rest of the trophic levels, including fish larvae and seabirds (Leppäkoski & Olenin, 2001). But with the increase in sea temperatures, the plankton blooms are earlier in the spring, but other species like herring still spawn at their traditionally determined time. The availability of plankton earlier does not follow the time of larvae hatching of the fish and the larvae enjoy less survival hence it disturbs the food chain (Karjalainen et al., 2007). This introduction presents a history of the importance of these climate induced changes in the triggers of the interactions among species in the Baltic Sea ecosystem causing considerable ecological implications (Sandberg, 2007; Viitasalo & Bonsdorff, 2022). The insights of these changes are essential in determining the effects of the changes on biodiversity, food web interactions, and ecosystem stability in the area.

Key Contribution

- This study highlights how climate change is altering the timing of key biological events in the Baltic Sea ecosystem.
- It highlights the disruptive impacts of heterotrophic planktonic time mismatch between plankton blooms and fish spawning on the survival and reproductive performance of species.
- The study reveals the changes that are occurring in the composition of species and instability of ecosystems due to these shifts.
- The article demands adaptive approaches to management to reduce the ecological disturbances brought about by climate change.

This paper followed by the various sections, Section I describes about introduction about the specific topics, Section II describes about the longitudinal monitoring, Section III describes about climate and phenology of data integration, section IV explained about methods and materials, Section V explained about case study of impact of climate change on herring spawning in the Baltic sea and broader ideas related to ecological impacts and also explained the future directions, Section VI Summarized the conclusion of the given topics.

Longitudinal Monitoring

The longitudinal monitoring methodology would be used to monitor the change in the life-cycle events of chosen species in the Baltic Sea ecosystem by considering the most important life-cycle events such as spawning, migration and

breeding. This is of the essence in the interpretation of the impact of climate change on species phenology in the long run. To have this, several fieldwork equipment will be utilized in the study. Marine mammals and fish will be monitored by using GPS which will allow them to determine the migration patterns and breeding areas that have changed. The sensors will be used to ensure that variations in the water temperature at different levels are monitored since temperature is an important factor in the life-cycles of the species (Ramya & Geetha, 2025). Data on the plankton population will be obtained using phytoplankton and zooplankton sampling kits as it is one of the important indicators of food availability in the marine food web. Also, larger mammal tagging equipment will be used to track animals over a long period to gain insight into their movements and adjustments to altered environmental conditions. The collection of data seasonally will be done over a matter of years, and this will mean that there will be extensive tracking on species in relation to different seasons of the year. The observation will be of species that are extremely sensitive to the environmental changes, like herring, cod, anchovy, seals, and migratory birds (Korpinen et al., 2012). Field visits will be undertaken frequently to document the time of the important life-cycle events, including the occurrence of the plankton blooms, fish spawning, and the time when migratory birds arrive. The data that will be obtained will be processed to see whether there will be any changes in the timing of these occurrences or not and the year-to-year data will be compared to identify the changes caused by climate. This will include matching of the

environmental variables such as temperature, salinity and ice cover to the biological data to identify the factors that modify the changes in phenology. It will apply the technique of predictive and agent-based modeling, in which historical data would be used to predict the speciation of species relationships and ecosystems in the future (Ramya & Geetha, 2025). The time-span of the monitoring also guarantees that the gradual patterns and changes are measured, which would give a better insight into the long-term effects of climate change on the Baltic Sea ecosystem (Neumann, 2000; Korpinen et al., 2012). This method will provide useful information to the impacts of climate change on species interaction and timing through a combination of fieldwork, technology, and data analysis, which will eventually be used to inform conservation and management approaches to the Baltic Sea.

Climate and Phenology Data

Integration

The purpose of the Climate and Phenology Data Integration approach is to merge the environmental data (e.g. temperature, salinity, ice cover) with biological data (e.g. breeding times, migration patterns) to learn what impact the change of climate has on the life cycle of species living in the Baltic Sea. Climate models, phenological tracking system and databases are some of the essential materials required in the comparison of past and current data (Karjalainen et al., 2007; Roslin et al., 2021). The methodology will entail gathering of environmental and biological data, their combination into a single database and statistical

instruments to evaluate correlations and identify the changes in the phenology of species with time. Advanced predictive models and ecological simulations will be used to predict the future effects and alterations in species interactions and food web dynamics (Forsblom et al., 2024). This combined strategy will assist in detecting changes caused by the climate such as changes in the seasons of breeding and migration. It will also educate efficient conservation and management policies of ecosystems. Moreover, the climate-insect interaction model will be used to forecast the pest outbreaks, being grounded on the degree-day accumulation, and will offer the information on possible ecological disturbances (Abduljaleel et al., 2025).

Figure 1 describes global climate change as the initiator, which results in warmer sea surface temperature (SST), reduction in freshwater inflow, and warmer winters. These climatic conditions cause major ecological changes to both the primary producers and consumers. This is characterized by particularly higher zooplankton peaks and earlier spring blooms which cause timing changes in major biological processes like phytoplankton/zooplankton peaks. This disturbance causes a trophic imbalance between the master producers and their eaters, such as fish and seabirds, which have comparatively stationary or less-shifted timetables for events like fish hatching and seabird hatching. This disharmony between the predators and their prey reproductive cycles has a tremendous impact on the success of the foraging activities, the reproductive success, the survival rate, and the stability of the proximal

ecosystem. Such disturbances may result in changes in species preeminence and ecosystem volatility which eventually affect disruption of species associations and ecosystem processes in the Baltic Sea. The diagram underlines that the

changes in phenology caused by climate have ripple effects on the entire ecosystem, and the long-term effects of these changes on biodiversity and food web dynamics are possible.

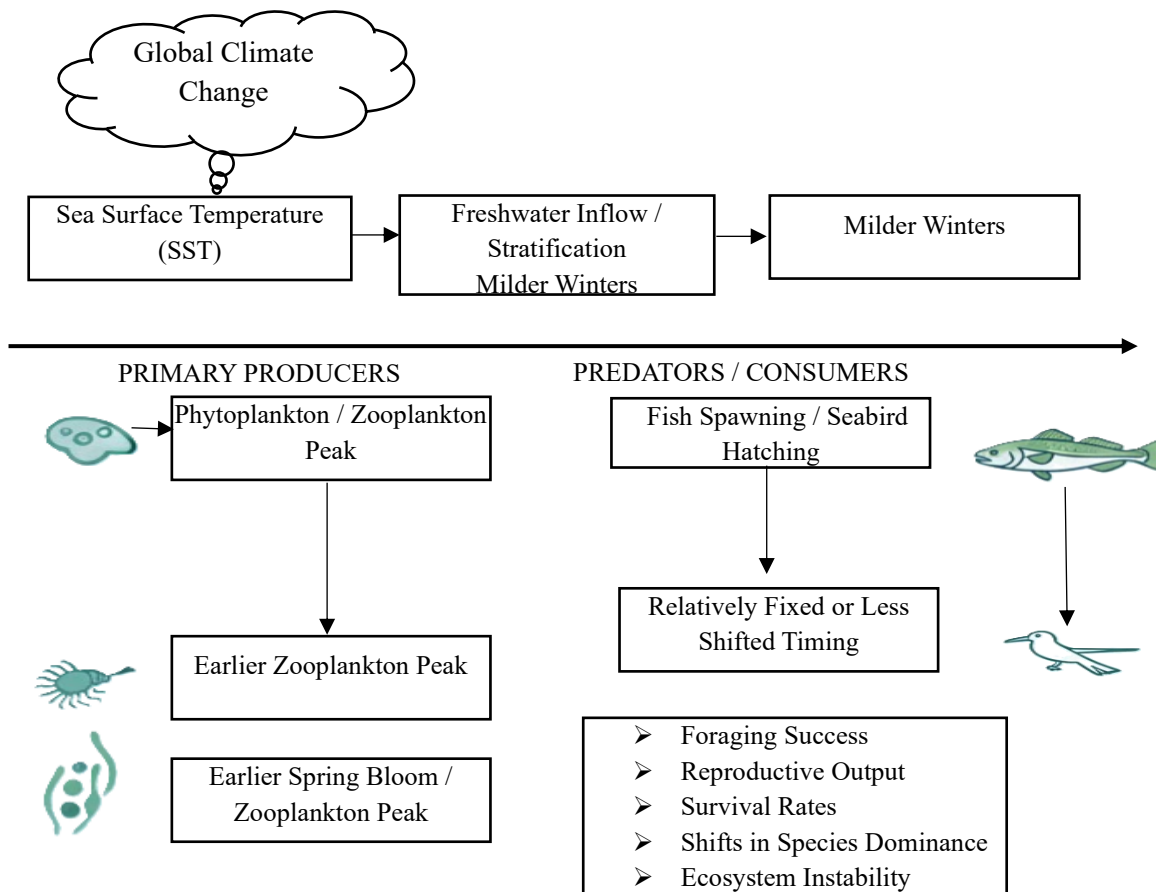


Figure 1: Overall Diagram about Climate-Induced Phenological Shifts and the Disruption of Species Interactions in Baltic Sea Ecosystem

Methods and Materials

This research would be based on satellite environmental data like the Sea Surface Temperature (SST) data of MODIS (Moderate Resolution Imaging Spectroradiometer) and NOAA (National Oceanic and Atmospheric Administration) that would monitor changes in temperature with time and give information on how the warming is affecting the time of biological occurrences. Also, the data regarding sea ice concentration provided by other agencies

such as NASA and ESA will provide important details on the effects of the dwindling cover on the life cycles of species in the Baltic Sea. Alongside this, the real-time environmental information will be given by in-situ monitoring stations like oceanographic buoys that will measure parameters such as temperature, salinity, and oxygen levels, which would be important in determining local variations and their impact on species phenology. On the biological aspect, historical ecological information of organizations

such as the Baltic Marine Environment Protection Commission (HELCOM) and the International Council of the Exploration of the Sea (ICES) will provide a reference point on how species population trends according to season and changes in their timing with climate changes will be used to derive the changes in their population patterns. Also, primary data will be collected using field equipment, such as plankton nets to sample zooplankton and phytoplankton, which will give data about the changes in the timing of primary and secondary producers. GPS monitors and satellite tags will be applied to marine species (e.g., fish and marine mammals) to trace their migration patterns, seasonal behavior, and underwater cameras and hydrophones will be used to observe interactions between predators and prey, enabling researchers

to predict how disrupted phenology is changing species interactions and food webs. Ecological modeling tools (e.g. Ecosim and AquaMaps) will be employed to simulate the impacts of changes in phenology on ecosystem dynamics so that the researchers can predict how food webs, species interactions, and overall ecosystem stability will vary in response to these. Such a holistic approach will provide further data on the study by adding reports of HELCOM, ICES, and other governmental or environmental organizations that will further validate the relevance of the study to ongoing research paradigms and reveal the nature of the interactions between climate change and species as well as species-species interactions in the Baltic Sea that will ultimately lead to the long-term health and stability of the ecosystem.

Table 1: Analysis of Climate Induced Phenological Shifts and the Disruption of Species Interaction in the Baltic Sea Ecosystem

Climate Driver	Impact on Primary Producers (Prey)	Impact on Consumers (Predators)	Disruption of Species Interactions	Ecological Consequences
Global Climate Change	Rising Sea Surface Temperatures (SST) lead to earlier peaks in phytoplankton and zooplankton populations.	Timing of fish spawning and seabird hatching remain relatively unchanged.	Trophic mismatch occurs when plankton become available earlier than predators can consume them.	Decreased foraging success, reproductive output, and survival rates of consumers.
Increased SST	Earlier zooplankton peak; shifts the timing of spring blooms.	Adjusted timing for fish spawning and seabird hatching.	Discrepancy between prey abundance and predator reproductive timing.	Changes in species dominance and ecosystem structure instability.
Triggering Phenological Shifts	The earlier zooplankton peak leads to a mismatch with predator spawning foraging.	Fish and seabirds might struggle to adapt to changes in food availability that occur earlier than usual.	Disrupts predator-prey interactions; feeding times become misaligned.	Leads to species extinction risk, imbalanced populations, and ecosystem disruption and degradation.

The Table 1 summarizes the consequences, through the phenological changes due to climate, on species interaction in Baltic Sea ecosystem, in

terms of how the alterations in climate drivers impact primary producers (prey) and consumers (predators). Phytoplankton and zooplankton

early blooms are caused by global climate change, which includes rising sea surface temperature (SST), warmer winters, and freshwater inflow changes, which shift the timing of food. Nevertheless, there is a relatively fixed time of the year when predators such as fish and seabirds reproduce resulting in a trophic mismatch whereby the predators do not have access to prey at a specific time of their lives. These changes in turn induce changes in the dominance of the species which result in the destabilization of the food web and hence instability of the ecosystem. The destabilization of predators-prey interactions and changes to food web processes have additional ecological effects, which are reflected in general ecological effects, such as the loss of biodiversity and imbalances in populations. Altogether, the table demonstrates that changes in the timing of the biological events due to the climate cause species interaction disruptions and destabilize the whole ecosystem in terms of its health and resilience.

Discussion

Climate change has been seen as one of the greatest causes of ecological disturbance in the world especially in marine environments. In the Baltic Sea, increasing temperatures, salinity, and ice-cover changes have resulted in changes in the timing of biological occurrences, or phenology, of both primary producers (e.g. phytoplankton) and secondary consumers (e.g. fish and seabirds). Such phenological changes have led to a trophic mismatch whereby the timing of various essential biological events no longer match each other to cause disequilibrium in the relationship of the species to each other and their ecological roles.

Among the most vivid examples of this phenomenon in the Baltic Sea is the malfunction of the plankton blooms timing and the consequent effects it had on the fish and seabird populations. The bottom of the food web is usually occupied by phytoplankton and zooplankton which supply nutrients required by the rest of the trophic levels. Nevertheless, climate change has resulted in earlier plankton blooms that were mainly caused by warming waters and earlier ice melt. This has been observed to interfere with the schedules of fish spawning which is typically later on in spring. Fish species plankton bloom serves as a source of food to fish species in the larval stages like herring. In situations where the bloom is earlier than normal, the newly hatched fish larvae could be short of the nutrient-rich planktons, or may find them in inadequate quantities and this lowers their survival chances.

Case study 5.1: The Effect of Climate Change on Herring Spawning in the Baltic Sea

An individual case study of such disruptions caused by climate is the change in the herring spawning periods in the Baltic Sea. Historically, herring have spawned at the end of the spring when the phytoplankton bloom had taken place. Nevertheless, a study that was carried out by the Baltic Marine Environment Protection Commission (HELCOM) has indicated that herrings have been found spawning earlier in the year as sea temperatures become warmer. Although this change of time can be explained by adaptive reaction to the environmental signals, it has resulted in the unclear correspondence to the

plankton bloom. The peak of the plankton is experienced occasionally ahead of the hatch of herring larvae and as such, the larvae lacks resources at a crucial point of their growth. This trophic disconnect has extensive repercussions. The premature hatching has thrown off the food web since herring constitute an important prey to many predators including seabirds, cod and seals. As an example, seabirds that depend on early availability of fish to feed their chicks at the nesting season might end up having inadequate preys, and consequently low reproductive

success, and in other instances, a decrease in population. The cod population - which greatly relies on herring as one of the main food sources - has also had to deal with changes in predator-prey interactions in which the timing of the plankton bloom no longer coincides with the timing of their breeding, thereby altering the species composition. An example of these timing discrepancies is the fluctuating population of the cod, which not only leads to the behavior of this organism, but also the entire ecological balance in the Baltic Sea.

Table 2: The Impact of Climate Change on Herring Spawning in the Baltic Sea

Climate Factor	Temperature Change (°C)	Ice Cover Change (Weeks Earlier)	Plankton Bloom Change (Weeks Earlier)	Salinity Change (PSU)
Rising Sea Temperatures	0.5	1	1	1.2
Changing Ice Cover	0.2	2	1.2	1.4
Earlier Plankton Blooms	0.3	4	1.5	1.45
Altered Salinity	0.4	3	1.8	1.5

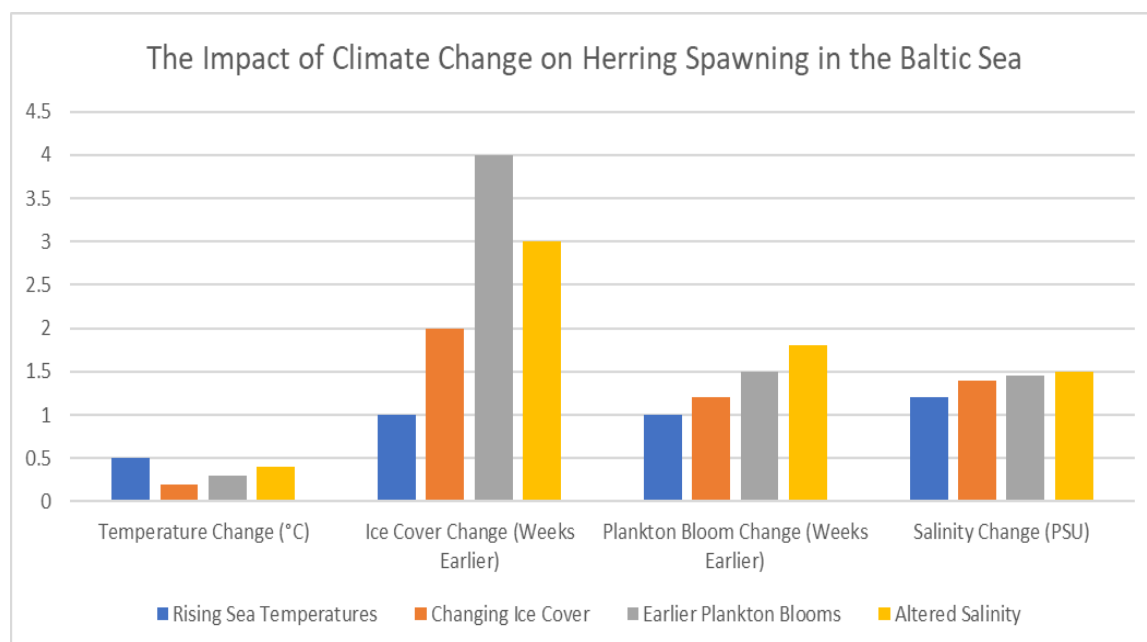


Figure 2: The Impacts of Climate Change on Herring Spawning In The Baltic Sea

The Table 2 and Figure 2 outlines the effects of the climatic change on different environmental conditions that influence the herring spawning in

the Baltic Sea but specifically the variations on sea temperature, ice cover, the timing of the plankton bloom and the salinity levels. The

increase in sea temperatures has contributed to the finding 0.5 °C rise, which has resulted in 1 week earlier ice cover, 1 week earlier plankton blooms, and 1.2 PSU salinity rise. The changes are pointing at the fact that the increase in temperature is causing earlier changes in the environment that may cause a disruption in the cueing mechanism of the herring spawning and food availability to the herring larvae. Shifting ice cover has been associated with a 0.2 °C increase in sea temperature, 2 weeks prior ice melt, 1.2 weeks prior plankton brightenings and a 1.4 PSU salinity change. This previous melting of ice and change in salinity can impact the appetite of herring toward their environment of breeding and distort the period of plankton blooms which the larval fish consume. With the warmer water of 0.3 °C, the change in ice melt of 4 weeks, plankton bloom of 1.5 weeks and 1.45 PSU salinity have been observed, further reducing the mismatch of the plankton blooms and fish spawning. This distortion can result in food shortage to the herring larvae at a very crucial age which can influence their survival. Finally, the 0.4 degree C rise in temperature, 3 weeks earlier ice melt, 1.8 weeks earlier plankton blooms, and 1.5 PSU shift in salinity have also been as a result of the altered salinity, which is yet another way of highlighting the disturbances that have taken place in the Baltic Sea due to warming and salinity variations, which affects the timing of ecological events. These aspects all point to the fact that the changes occurring due to the climate are leading to an unnatural mismatch in troic cascades, which affects herring spawning and the food of herring larvae, as well as other ecological imbalances in the Baltic Sea

ecosystem. Adaptive management strategies are needed to ensure that these effects are controlled to ensure stability in the ecosystems.

Broader Ecological Impacts

The ecological implications of the consequences of the broken species interactions through phenological shifts are even wider. Cascading effects of a disturbance in predator-prey interactions that can be evidenced by the herring-cod interactions can result in extreme species extinction, especially to specialized predators that lack a wide range of prey. Moreover, the alteration in species interactions might also result in the changes to the Baltic Sea ecosystem structure since some species might adapt well to new conditions whereas others will not be able to cope. An example of this would be the fact that more warm water species have been seen, as a consequence of warmer waters and the rise in the plankton blooms occurring earlier. These species tend to out compete native species and hence cause changes in biodiversity because these species will be guided by different timing or environmental conditions. This may also have additional impacts on the ecosystem services, including nutrient cycling and water quality control, which is dependent on a balanced food web and healthy species interaction.

Future Directions

The response to the effects of climate-driven changes in the phenology of the interactions in the Baltic Sea should be multi-layered, and the following areas of concern represent the resolutions of future studies and management. It is necessary to monitor phenological shifts in the

long term continuously to have more insight into the dynamics of the changes and their relations to environmental changes. This has been made possible by incorporating satellite data, remote sensing and in-situ monitoring in areas of under-sampling and species that are challenging to monitor. More ecological models, which reproduce the impacts of the climate change on species interactions and food web processes in the Baltic Sea are also important in estimating future changes and their impacts on biodiversity and ecosystem services. Both the climate projections and species phenology have to be included in these models so that they can help in guiding the future management decisions in the fisheries industry and conservation efforts. This involves changing the fishing quotas, fishing seasons, and marine protected areas (MPAs) to consider the changing distribution and spawning of species. Moreover, conservation plans must be modified to meet the shifting timings of the species, and even the MPAs may have to be restructured so that the areas of critical habitat can be conserved. The process of restoration, which is targeted at improving ecosystem processes, like seagrass bed and coastal wetland restoration processes, will also help to establish resilience when faced with climate-induced disturbances. Such plans coupled with attempts to minimize the anthropogenic stressors such as overfishing and pollution will stabilize the ecosystem and enhance species adaptability to the climate change. Policies and policy development as well as public awareness also have significant roles to play in resolving these challenges. Sensitization of the general population on the impacts of climate change on

the Baltic Sea ecosystem, community involvement, and building stakeholder cooperation will also be essential in attracting support towards conservation and adaptation efforts. The stakeholders in the fisheries policies, marine spatial planning and environment protection policies should incorporate the effects of climate change into policies in order to have adaptive strategies. Lastly, global collaboration and inter-regional research will also come in handy to find out the global impacts of climate-induced changes and exchange ideas to assist in curbing the same in other marine ecosystems. In conclusion, future studies and management ought to concentrate on enhancing our knowledge on these changes, their environmental effects that are likely to be forthcoming, on the strategies to adapt to the changes brought about by the climate changes in the Baltic Sea and other regions.

Conclusion

Phenological changes in the Baltic Sea ecosystem due to climate are causing a major change in the timing of vital biological processes, including fish spawning, bird migration, and plankton bloom. These shifts, which are mainly caused by the increase of the sea temperature, salinity, and the alteration of the ice cover, are interfering with the coordination of the interactions between the species. Among the most prominent is the disconnect between the previous plankton bursts and the restrictions in the reproduction cycle of fish, especially herring, in that trophic mismatch occurs where a given trophic level, such as fish larvae, seabirds, and marine mammals, has inadequate food available. This results in decreased survival, decreased

reproductive success and wider disturbances of predator-prey interactions. These climatic shifts on the environmental front can be seen in the fact that the sea temperature is rising by 1.2 °C, the length of the ice cover has been shifting by 1.4 weeks earlier, the plankton is blooming earlier by 1.45 weeks, and the salinity has become 1.5 PSU higher. Such changes also make the ecosystem unstable, and species are unable to adjust to the new environment. The associated disproportions of species structure and ecological processes underline the necessity of the adaptive management approaches. The strategies to be used should center on ongoing monitoring, the adaptable conservation process, and incorporation of the climate change projections into the policy frameworks. Overcoming these obstacles will also be central to maintaining the health and strength of the Baltic Sea ecosystem, despite the current climate change experienced.

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