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Climate Change Effects in the Baltic Sea and the Black Sea – an adaptation perspective

Science Brief

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Table of Contents

Introduction	3
1. Baltic Sea	5
1.1 The ecosystem perspective	5
1.1.1 Summary of climate change related effects	5
1.1.2 Adaptation needs	7
1.2. Catchment area effects	9
1.2.1 Projected impacts	9
1.2.2 Adaptation needs	11
2. Black Sea	13
2.1 The ecosystem perspective	13
2.1.1 Summary of climate change related effects	13
2.1.2 Adaptation needs	14
2.2. Catchment area effects	15
2.2.1 Projected impacts	15
2.2.2 Adaptation needs	16

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Cover photo: Seagrass (*Zostera marina*) at Dzharylhach Island in the Black Sea. Credits: Sofia Sadogurska

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Introduction

Efforts to reduce greenhouse gas emissions need to continue and strongly intensify in order to reduce the effects of climate change. It is, however, clear that these effects are strongly present already at the current level of climate change in marine and coastal areas around the world¹.

Climate change is already altering the physical, chemical, and biological conditions of regional seas across Europe, including the Baltic Sea and the Black Sea. Rising sea surface temperatures, changes in precipitation patterns, more frequent marine heatwaves, sea-level rise, and shifts in storm intensity are affecting both marine ecosystems and the coastal communities that depend on them. These changes influence species distribution, ecosystem productivity, water quality, fisheries, and the provision of ecosystem services. At the same time, climate change interacts with existing environmental pressures such as pollution, eutrophication, habitat degradation, and overexploitation of marine resources, amplifying their impacts and creating additional challenges for sustainable management and adaptation.

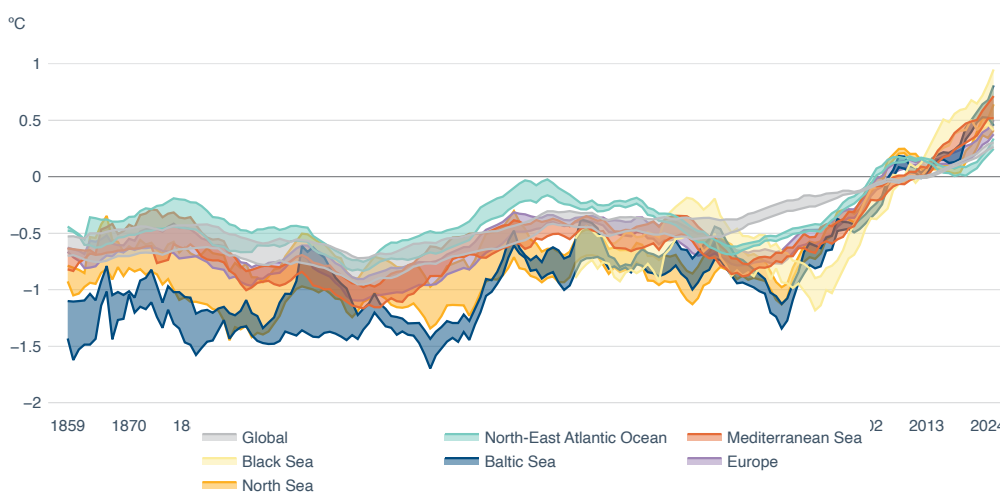


Figure 1. Decadal average sea surface temperature anomaly in different European seas. EEA (2025).

According to HELCOM, climate change effects in the Baltic Sea include, for instance, rising water temperatures and decreasing ice extent. Increasing annual mean precipitation occurs in the northern parts of the Baltic Sea region.² The changes have marked effects on the ecosystems and the ecosystem services. The direct and indirect effects of climate are in themselves complex, and the complexity is further enforced by feedback mechanisms and interactions between climate change effects and other environmen-

1 IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

2 HELCOM: <http://stateofthebalticsea.helcom.fi/findings/pressures/climate-change/>

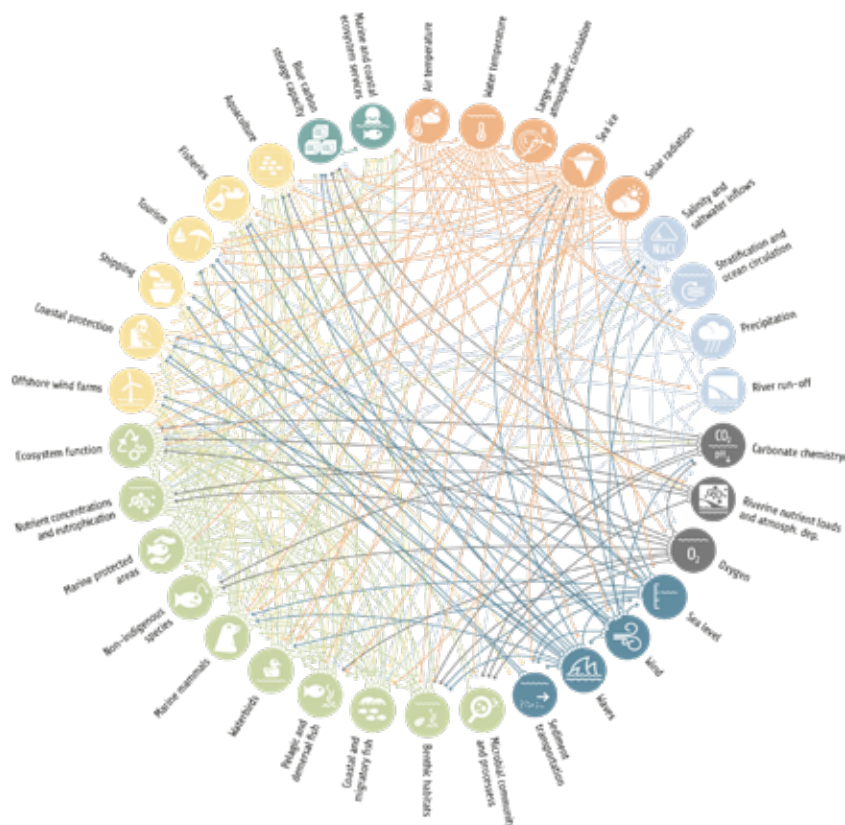


Figure 2: The Baltic Sea is facing complex effects and feedbacks between climatic and non-climatic factors, as well as between the effects of climate change on different parts of the ecosystem. Source HELCOM/Baltic Earth 2021.

tal changes (Figure 2). The Black Sea is particularly vulnerable to climate change due to its semi-enclosed nature, limited water exchange with the Mediterranean Sea, and extensive river catchment. Observed and projected climate change impacts include increasing sea surface temperatures, more frequent and intense marine heatwaves, changes in precipitation and river runoff, sea-level rise, and alterations in water circulation patterns. These changes can affect the structure and functioning of marine ecosystems, contribute to shifts in species composition and distribution, increase the risk of invasive species expansion, and exacerbate existing pressures such as eutrophication, coastal erosion, and biodiversity loss. Climate-driven changes in the Black Sea are also expected to have significant implications for fisheries, coastal infrastructure, tourism, and the livelihoods of communities across the region.

Given that these direct and indirect effects are ongoing – and predicted to increase even within the most optimistic climate change scenarios – it is clear that adaptation measures are needed alongside continued mitigation efforts. These adaptation measures need to be based on not only an understanding of the current state, but also on projections of future effects.

In this briefing, these projections are viewed from two separate, but interlinked, perspectives, namely:

1. The ecosystem perspective
2. Catchment area effects

1. Baltic Sea

1.1 The ecosystem perspective

1.1.1 Summary of climate change related effects

This section summarises ongoing and predicted climate change effects on Baltic Sea aquatic ecosystems, communities, and species^{3, 4}. In addition, effects of ocean acidification are briefly described.

Fish: Cod stocks in the Baltic Sea peaked in the early 1980s, as a combination of favorable oxygen and salinity conditions (thanks to a series of large inflows of saline and oxygen rich water from the North Sea⁵), relatively low fishing pressure, as well as low predation by seals. Since then, however cod stocks have seriously suffered from unfavorable oxygen and salinity conditions (also driven by eutrophication). Hence the so called “cod reproductive volume” where cod spawning can occur has been seriously limited. Poor growth of cod has furthermore been observed, which has been attributed to low food availability and/or physiological factors caused by poor oxygen levels. Moreover, as the review concludes: “At a critical moment, fisheries management failed to fully consider the changed environmental conditions, and climatic factors now prevent the recovery of cod stocks.” As cod reproduction is also affected by ocean acidification (see separate section below), the overall projections for cod are bleak.

Other economically and ecologically important fishes, such as sprat could benefit from climate change, due to higher temperatures in spring and summer. These increased temperatures have been observed to be beneficial for the survival of sprat eggs and larvae, and increased productivity has also been suggested. For herring, a “net effect” of climate change together with other drivers is difficult to predict. Whereas the growth rate of herring is favored by higher temperatures, availability of food (especially marine copepods; see section on plankton) and competition with sprat may counteract positive effects.

Deep benthic communities⁶: The food conditions of the zoobenthos, i.e., the animals living at the sea bottom, are dependent on the production in the water column, which through sedimentation eventually provides resources to these animals. Oxygen conditions form another decisive factor for zoobenthos, and these conditions are interlinked with production and sedimentation (the more sedimentation of organic

3 As interpreted for the current briefing

4 Viitasalo, M. and Bonsdorff, E.: Global climate change and the Baltic Sea ecosystem: direct and indirect effects on species, communities and ecosystem functioning, *Earth Syst. Dynam.*, 13, 711–747, <https://doi.org/10.5194/esd-13-711-2022>, 2022

5 These inflows are by themselves affected by climate change, though rising North Sea sea levels on the one hand, and increased fresh water inflow on the other hand. Projections on the balance between these phenomena that counteract each other are as yet uncertain. Please read more here <https://balticwaters.org/en/deep-dive-the-inflows-that-shape-the-baltic-sea/>

6 Those occurring at the sea bottom

matter, the higher the oxygen consumption resulting from consumption by zoobenthos and microorganisms). Hence, projections regarding benthic communities are strongly dependent on future developments for nutrients. Continued reductions in nutrient levels would first lead to higher biomass of zoobenthos, thanks to improved oxygen conditions. However, decreased production would eventually have the opposite effect. Another aspect of benthic communities is the establishment of non-indigenous species, which is coupled to and facilitated by climate change. It is worth noting that drastic changes in benthic communities have already taken place as an interplay between temperature, oxygen, eutrophication, invasive species, as well as salinity. It is also worth noting that the composition and biomass of zoobenthos is highly important for the fishes that feed on these animals.

Shallower parts in the Baltic Sea⁷: Macroalgae – and especially bladderwrack – that dominate in these parts may suffer from overgrowth by epiphytes⁸, due to heatwaves. This phenomenon is similar to effects caused by eutrophication. In the case of heatwaves, the underlying mechanism is that invertebrates that feed on the epiphytes suffer from the heatwaves, which favour the growth of these epiphytes. In addition, a decrease in salinity is a possible (but as of yet uncertain) effect of climate change. If salinity decreases, marine species (e.g., bladderwrack, eelgrass and blue mussel) would suffer. Freshwater plants would benefit, but they cannot compensate for the loss of macroalgae on rocky substrates.

The open sea – plankton: As for phytoplankton, the most evident effect of climate change is that the growing season is getting longer. Other effects, however, are species- and area-dependent, i.e., effects are difficult to generalise. Projections based on models suggest that the spring bloom of phytoplankton would decrease, whereas cyanobacteria blooms in summer would become stronger. A negative effect of increased cyanobacterial blooms that fixate nitrogen would be an increased ratio of phosphorous to nitrogen, which would strengthen the “vicious circle of eutrophication”⁹. There are, however, conflicting results based on both field- and experimental studies with regards to the response of cyanobacteria to climate change related factors.

Bacteria are an important component of the plankton food web, and climate change effects that favour bacteria growth include a projected increase of riverine dissolved organic matter (DOM) as well as warming. However, the complexity of interactions in the microbial food web makes it hard to predict the effects of DOM and warming. Similarly, increased DOM could decrease primary production, but the authors conclude that the resulting changes are as of yet not well understood for different areas of the Baltic Sea.

More conclusive predictions can be made for zooplankton, for which warmer springs accelerate growth. The time lag that occurs between the spring phytoplankton peak

7 Where there is enough light for photosynthesis

8 Plants or plant-like species that grow on other plants or plant-like species

9 See e.g., https://indicators.helcom.fi/wp-content/uploads/2023/04/Cyanobacterial-bloom-index_Final_August.pdf, p. 5

and the peak of the zooplankton that feed on them will become shorter. As a result, phytoplankton biomass may be reduced in spring. The composition of zooplankton is predicted to shift towards smaller sizes and a reduction in marine copepod species.

A note on ocean acidification¹⁰: The projected mean reduction of pH in the Baltic Sea by the year 2100 ranges from 0.1 to 0.4 units, depending on the success of mitigation measures.¹¹ We have previously reported on effects of ocean acidification on species and ecosystems in two publications^{12,13}. Clearly, these effects are intertwined with direct and indirect effects of warming. Here, we briefly mention some of the most conclusive effects, with emphasis on implications for adaptation needs.

Negative effects have been observed on the bivalve *Limecola balthica*, which is a key species in large parts of the Baltic Sea. Another keystone bivalve species is the blue mussel. Here, negative effects have also been reported, although they are believed to be counteracted by adaptive properties that evolve under fluctuating pH-conditions. In the case of zooplankton, acidification effects on the marine copepod *Acartia* have been observed; these effects included “buffering responses” consisting of changes in size and offspring. As for fish, negative effects have been observed on e.g., cod, especially with regards to the western Baltic Sea population. It is worthwhile mentioning that a study based on recruitment models suggested that cod recruitment could be reduced to just 8 % of current levels under end-of-the century pH-conditions (IPCC RCP 8.5)¹⁴.

A potentially important observation from an adaptation and conservation perspective is that pH-levels are by default higher in locations with high levels of photosynthesis, where CO₂ is taken up by the photosynthesising organisms. These locations include seagrass meadows and macroalgal belts, such as those formed by bladderwrack.

1.1.2 Adaptation needs

Here, we briefly discuss and highlight the adaptation needs from the perspective of aquatic ecosystems in the Baltic Sea.

Firstly, it is important to note – as is commonly the conclusion in studies on climate change effects in the Baltic Sea – that the region is facing multiple human-introduced pressures that occur in tandem with climate change and ocean acidification. These include eutrophication (due to excess nutrients), pollution, over-fishing, and erosion¹⁵, to name a few.

10 Ocean acidification is the result of excess CO₂ taken up by seawater. It is sometimes called the “equally evil twin of climate change” and is just like global warming the result of burning of fossil fuels. The resulting decrease of seawater pH is especially affecting calcifying organisms

11 <https://www.su.se/english/divisions/stockholm-university-baltic-sea-centre/news/articles/2024-02-15-baltic-breakfast-ocean-acidification---an-emerging-problem-also-in-the-baltic-sea>

12 https://www.airclim.org/sites/default/files/2025-05/ocean-acidification-in-the-baltic-sea-apc-40_0.pdf

13 https://www.airclim.org/sites/default/files/document/country_report_on_ocean_acidification_country_for_sweden.pdf

14 <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0155448>

15 In part driven by climate change effects

Secondly, and as also highlighted in the review cited in the section on ecosystem effects, several knowledge gaps remain in relation to climate change projections. These include future salinity levels, internal loading of nutrients¹⁶, stratification conditions¹⁷, food web interactions, etc. As indicated previously, the future “balance” between freshwater inflow and North Sea sea levels – as driven by climate change – which is crucial for the occurrence of saline and oxygen rich inflows from the North Sea also remains unclear. This last factor of course interacts with many of aforementioned physico-chemical factors, underscoring the fact that projections on several decisive conditions either cannot be made at present, or at least that several different trajectories are possible.

Nevertheless, some important conclusions on adaptation needs can be made, especially from ecosystem and conservation perspectives.

Eutrophication: Continued nutrient abatement needs to remain a focal point in Baltic Sea management. The study cited above concludes that climate change may slow down the results of ongoing efforts to reduce nutrients, but also that these reductions will eventually be even a stronger driver than climate change. Given the interactive effects between eutrophication and climate change, and the strong ecosystem effects that are affected by both drivers, such as reductions in the “cod reproductive volume” and overgrowth of macroalgae in the littoral zone, it is clear that changing the course of eutrophication must be an integral part in adaptation measures.

This is especially true as climate change and eutrophication do not only interact in terms of effects. Indeed, climate change also affects the sources of eutrophication through drainage area effects. Factors that need to be considered in this context include increased precipitation, floods, stormwaters and erosion.

Marine Protected Areas (MPAs): Given the multiple drivers that critically threaten Baltic Sea species and ecosystems, it is clear that the importance of traditional protection and conservation measures cannot be overstated in the context of adaptation measures. The rationale is that additive and synergistic negative effects need to be minimised, even if direct effects of warming (including heat waves) cannot be avoided (although they need to be forcefully mitigated, and their magnitude will depend on the success of mitigation measures globally).

MPAs can provide refugia where at least effects of local drivers minimised. For instance, seagrass meadows and macroalgal communities that are compromised by overgrowth and high turbidity due to eutrophication will benefit if they are protected from mechanical disturbances from boating, dredging, trawling etc. If these MPAs are properly considered in marine spatial planning, extended benefits can be obtained e.g.,

16 Especially phosphorous that is released from sediments under poor oxygen conditions, in part maintained by eutrophication

17 The water column is permanently stratified in a less saline surface layer and a more saline bottom layer in deeper areas that cover a vast part of the Baltic Sea; in addition, thermal stratification occurs in summer, when denser and colder deeper water is separated from a warmer surface layer. Both phenomena hinder the transport of oxygen rich surface water to the deeper layers hence resulting in poor oxygen conditions

in reductions of nutrients from both point and diffuse sources. This kind of healthy habitats are beneficial for e.g., fishes that rely on such locations for feeding, spawning and cover. These areas could also provide refugia where pH is locally higher than in surrounding areas, which would counteract effects of ocean acidification. Similarly, deeper areas need to be protected for the benefit of healthy benthic communities, as well as fishes and other predators that depend on these communities for food. Apart from direct benefits, it is generally accepted that a high level of biodiversity is beneficial for the capacity of ecosystems to withstand and recover from disturbances.

Marine spatial planning and establishment as well as management of MPAs should additionally pay special attention to spawning areas of fish, including the recognition of the currently strongly diminished “cod reproductive volume”.

Given the complexity among drivers as well as within ecosystems, a specialised tool has been developed in Sweden for ecosystem based marine spatial planning¹⁸; the tool can be used in other countries as well.

Fishing: An ecologically straightforward low-hanging fruit to compensate for negative consequences of climate change, ocean acidification and other drivers is the regulation of fisheries to levels that populations can withstand and that guarantee the size and age structures of fish populations that is needed for viable reproduction. Politically and societally such regulations are far from straightforward, and scientifically solid arguments for sustainable fisheries are regularly watered down locally, nationally and at the level of the EU. Nevertheless, continued efforts, including forceful, evidence-based communication, are needed to meet this end. A solid argument in this context is the long-term benefit for fisheries that could be achieved via sustainable catch levels¹⁹. Indeed, catch volumes over time can be much higher if scientifically sound regulations can be applied.

1.2. Catchment area effects

1.2.1 Projected impacts

Fourteen countries are represented within the catchment area of the Baltic Sea. Nine of these are HELCOM member countries, consisting of Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. Additionally, there are five transboundary countries, namely Belarus, Czech Republic, Slovakia, Norway and Ukraine. Five of these countries (Germany, Poland, Russia, Belarus, the Czech Republic, and Slovakia) in part also belong to the Black Sea catchment area, and climate change and other drivers can be partly viewed in an even larger context, encompassing

18 <https://maritime-spatial-planning.ec.europa.eu/practices/symphony-tool-ecosystem-based-marine-spatial-planning>

19 See e.g., <https://www.su.se/english/divisions/stockholm-university-baltic-sea-centre/stockholm-university-baltic-sea-centre/fisheries/analysis-baltic-sea-fishing-has-not-gone-according-to-multiannual-plan>

a corridor between these two inland seas. This also applies to adaptation measures.

Projected impacts have been thoroughly analysed in the Second Assessment of Climate Change (BACC II). Here, we very briefly summarise some of the findings²⁰ based on an updated review²¹, with focus on non-marine factors (which were dealt with in previous sections).

Precipitation: End-of-the century projections suggest increased annual mean precipitation, especially in winter. Instances of heavy rainfall are also predicted to increase. There is also some evidence for an increase in the number of dry days in southern and central parts of the basin in summer.

River runoff: There is a predicted increase of 20 % for discharge from rivers, however with differences between sub-basins. High flows are expected especially in autumn and winter. Larger runoff would also imply larger inflow of nutrients to the Baltic Sea, i.e., contribute to eutrophication.

Terrestrial growing season: A decreasing surface albedo²² is predicted to increase warming in winter and spring in the Arctic, whereas evapotranspiration is projected to have the opposite effect in summer. Vegetation growth will be stimulated by an earlier start of the growing season.

Snow: A strong reduction in snow – by more than 70 % – is predicted under RCP 8.5.

Glaciers: A loss by more than 80 % of the current mass is predicted by the end of the century for Scandinavian glaciers. Increased river runoff with earlier spring peaks is also predicted.

Permafrost: The loss of permafrost has already started and is predicted to increase.

Lake ice: Lakes already freeze later than before, and the ice breaks up earlier in spring, resulting in shorter periods of ice cover – these trends are predicted to continue.

Waterbirds: There is an ongoing trend of a northward shift in the distribution of waterbirds, which is predicted to continue. At the same time, rising sea levels and coastal erosion could compromise breeding habitats for these birds.

A note on coastal erosion: Whereas the assessment above concludes that from a predictive perspective, coastal erosion patterns are difficult to describe at present, it is obvious that this phenomenon, driven by climate change related factors – such as ris-

20 For confidence levels, please see reference

21 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., Gaget, E., Galatius, A., Haapala, J. J., Halkka, A., Hugelius, G., Hünicke, B., Jaagus, J., Jüssi, M., Käyhkö, J., Kirchner, N., Kjellström, E., Kulinski, K., Lehmann, A., Lindström, G., May, W., Miller, P. A., Mohrholz, V., Müller-Karulis, B., Pavón-Jordán, D., Quante, M., Reckermann, M., Rutgersson, A., Savchuk, O. P., Stendel, M., Tuomi, L., Viitasalo, M., Weisse, R., and Zhang, W.: Climate change in the Baltic Sea region: a summary, *Earth Syst. Dynam.*, 13, 457–593, <https://doi.org/10.5194/esd-13-457-2022>, 2022.

22 The fraction of sunlight that is reflected

ing sea levels, storm surges etc. – are important to consider in an adaptation context.²³ This applies especially to the southern coast of the Baltic Sea.

A note on forests and carbon sequestration: We have recently published a report on Northern Forests and climate change²⁴ as part of a larger project on this issue²⁵. Forests are evidently a vital component of the Baltic Sea catchment area. Summarising the findings of the report goes beyond the scope of the present briefing. It is, however, worthwhile noting here that whereas longer growth seasons and increased concentrations of CO₂ as such can be favorable for forest growth, there are several other climate change driven factors that work to the contrary. These include forest fires, pest outbreaks and storms (wind throws).

Some important species, such as beech, decline in large areas as a result of climate change. For boreal forests, there are tipping points that can become reality, or may locally already have been reached.

At the same time, rotation forest management and insufficient protection of forests diminish the biodiversity and climate mitigation potential of forests. In a projection perspective these observations are important in general as the carbon sink-source balance is delicate. Without proper management measures, forests are increasingly becoming carbon sources, whereas a transition to ecosystem-based management over the entire managed northern forest area could increase the annual carbon sink to a figure that corresponds to 20% of the present global forest sink. Of course, this figure is global, but nonetheless important to consider also in the context of forests in the Baltic Sea catchment area.

Another important point in terms of projections – and specifically in the context of catchment area processes that affect the state of the Baltic Sea – is the potential of healthy and diverse forests to retain nutrients. An extreme but widespread practice that works to the contrary is clear-cutting.

Overall, forest management and protection form a vital part for climate adaptation, including in relation to the Baltic Sea.

1.2.2 Adaptation needs

Clearly, most of the projected changes mentioned above cannot be directly tackled by adaptation measures. However, the effects of some of these can be subject to adaptation measures, specifically aiming at counteracting the effects on the Baltic Sea ecosystems.

23 <https://oxfordre.com/climatescience/display/10.1093/acrefore/9780190228620.001.0001/acrefore-9780190228620-e-897>

24 https://www.airclim.org/sites/default/files/2025-05/sink_or_source_report_250321.pdf

25 <https://www.airclim.org/projects/northern-forests-and-climate-change>

Nutrient abatement: Increased precipitation, river runoff, flooding, and erosion all act to bring more nutrients from the catchment area to the Baltic Sea – in the entire region from Poland, Slovakia, and Ukraine in the south to the Finnish and Swedish parts of Lapland in the north. A key factor in adaptation is the potential of vegetation to bind nutrients and/or eroding soil that would otherwise enter rivers or coastal waters. This can be achieved by spatial planning that includes protective vegetation zones along rivers in especially exposed areas. This approach also applies to appropriate choices of crops in agricultural areas. Wetlands can be constructed in or close to estuaries in order to bind nutrients before they enter the sea; this can also be applied to tributaries to larger rivers and to lakes that are important constituents in the drainage area dynamics. In addition, and as mentioned in the previous section, forest management plans need to consider the effects of forestry on nutrient dynamics in forest soils, aiming at minimising nutrient leakage.

Apart from these measures that mainly deal with binding of nutrients to soil and vegetation in rural areas, methods that properly address surface runoff need to be applied in cities and towns, aiming at reducing excess rainwater from eventually reaching watersheds or overloading wastewater treatment plants.

Coastal erosion: As mentioned in the previous section, coastal erosion needs to be seriously considered in an adaptation context, especially in the southern parts of the Baltic Sea. This applies both to erosion-prone rocky materials (i.e., limestone) and to shallow, mainly sandy beaches and dunes. Whereas protective measures for higher rocky shores may be difficult or impossible to apply (and adaptation would mainly consist of risk-assessments in relation to building and construction), the erosion in the latter can be at least partly controlled, although these environments are admittedly challenging as well. Erosion can be tackled with restoring or protecting natural vegetation that binds sand, and by constructions that either also prevent erosion or protect the shoreline from exposure.

There are, however, serious pitfalls that need to be considered. These include avoidance of introducing non-native species (which historically has been done either on purpose, or by introducing wooden stick fences the sticks of which have been able to take root and spread). Natural erosion processes also need to be considered – even without climate change effects dunes are naturally dynamic.

A more straightforward method is to counteract climate-induced erosion by minimising eroding pressure from visitors. Areas that are entirely protected from even pedestrians are needed, as well as restrictions on use of bikes and motor vehicles on the dunes. A prerequisite is that appropriate infrastructure (e.g., parking) is provided in suitable areas. In some areas, a fee is taken for entrance – in these cases the revenue should be directed to coastal protection, which is rarely if ever the case at present.

2. Black Sea

2.1 The ecosystem perspective

2.1.1 Summary of climate change related effects

The Black Sea is highly vulnerable to climate change due to its semi-enclosed nature, limited water exchange with the Mediterranean Sea, and strong dependence on freshwater inflows from a vast catchment area²⁶. Climate change impacts are stronger here than in many other parts of Europe: sea surface temperatures are increasing twice as fast as in the North Sea²⁷, while many pollutant concentrations exceed toxicity thresholds. The region is also vulnerable to sea-level rise and to industrial, chemical, biological, radiological and nuclear risks, posing significant threats to economies and livelihoods²⁸. These changes affect the physical and biogeochemical functioning of the sea and are expected to intensify throughout the 21st century.

Climate change is already influencing the distribution, abundance, and seasonal dynamics of marine species and habitats. Rising temperatures can alter species composition, favour warm-water and non-native species, and affect the productivity and resilience of key ecosystems. Fish populations may experience shifts in distribution, changes in reproductive success, and increased vulnerability to environmental stressors, with implications for fisheries and food security²⁹. Coastal ecosystems, including sea-grass meadows, macroalgal communities, lagoons, estuaries, and wetlands, face increasing pressure from warming waters, sea-level rise, coastal erosion, and extreme weather events.

Ocean acidification adds another climate-related pressure. Although the Black Sea differs from the open ocean due to its unique hydrography and carbonate chemistry, increasing atmospheric carbon dioxide concentrations are expected to reduce seawater pH and affect marine organisms that rely on calcification processes³⁰. Combined with

26 Celikyilmaz-Aydemir, G. (2012). Vulnerability of the Black Sea to the Impacts of Climate Change. In: Lagutov, V. (eds) *Environmental Security in Watersheds: The Sea of Azov*. NATO Science for Peace and Security Series C: Environmental Security. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-2460-0_10

27 European Environment Agency (2025). European sea surface temperature <https://www.eea.europa.eu/en/analysis/indicators/european-sea-surface-temperature>

28 EMBLAS Final Scientific Report (2022). Dnipro: Seredniak T.K., 2022 - 462 p. ISBN 978-617-8111-01-4. https://emblasproject.org/wp-content/uploads/2022/03/EMBLAS_Scientific-Report_ISBN-978-617-8111-01-4-web.pdf

29 FAO. 2023. *The State of Mediterranean and Black Sea Fisheries 2023 – Special edition*. General Fisheries Commission for the Mediterranean. Rome. <https://doi.org/10.4060/cc8888en>

30 Elge M., 2021. Analysis of Black Sea ocean acidification. *International Journal of Environment and Geoinformatics* 8(4): 467- 474. 10.30897/ijgeo. 857893

warming, deoxygenation, and nutrient pollution, ocean acidification may further reduce ecosystem resilience and alter food-web dynamics.

Climate change impacts interact with existing environmental pressures, including eutrophication, pollution, habitat degradation, overfishing, and biological invasions³¹. The ongoing Russian war against Ukraine has added further environmental risks through pollution from military activities, damage to coastal and marine habitats, disruptions to environmental monitoring, and increased pressures on coastal ecosystems.³² Together, these cumulative impacts reduce the adaptive capacity of Black Sea ecosystems and increase the urgency of coordinated adaptation measures.

2.1.2 Adaptation needs

Adaptation in the Black Sea should focus on strengthening the resilience of marine and coastal ecosystems while addressing the cumulative effects of climate change and other anthropogenic pressures. Ecosystem-based adaptation can help maintain biodiversity, ecosystem functions, and the services that support coastal communities and economic sectors.³³

Marine Protected Areas (MPAs) and other effective conservation measures will need to account for climate-driven changes in species distributions, habitat conditions, and ecosystem connectivity. This may require improving the representativeness and connectivity of protected area networks, enhancing monitoring systems, and incorporating climate projections into management and conservation plans.

The fisheries sector will require adaptive and ecosystem-based management that takes into account changing species distributions, stock productivity, and environmental conditions.³⁴ Strengthening scientific monitoring, improving regional cooperation, and increasing the flexibility of management frameworks will be important for maintaining sustainable fisheries under changing climatic conditions.

Reducing non-climatic pressures is another critical adaptation measure. Improved management of nutrient inputs, pollution, habitat degradation, and invasive species can

31 EMBLAS Final Scientific Report (2022). Dnipro: Seredniak T.K., 2022 - 462 p. ISBN 978-617-8111-01-4. https://emblasproject.org/wp-content/uploads/2022/03/EMBLAS_Scientific-Report_ISBN-978-617-8111-01-4-web.pdf

32 Kvach, Y., Stepien, C.A., Minicheva, G.G., P. Tkachenko (2025). Biodiversity effects of the Russia–Ukraine War and the Kakhovka Dam destruction: ecological consequences and predictions for marine, estuarine, and freshwater communities in the northern Black Sea. *Ecol Process* 14, 22. <https://doi.org/10.1186/s13717-025-00577-1>

33 United Nations Environment Programme (2021). *Adaptation Gap Report 2021: The gathering storm – Adapting to climate change in a post-pandemic world*. Nairobi. <https://wedocs.unep.org/items/bba9a0ad-c213-48ef-b039-c1d3c240a3b8>

34 FAO. 2023. *The State of Mediterranean and Black Sea Fisheries 2023 – Special edition*. General Fisheries Commission for the Mediterranean. Rome. <https://doi.org/10.4060/cc8888en>

strengthen ecosystem resilience and help buffer the impacts of climate change. Given the strong influence of riverine inputs on the Black Sea, adaptation efforts should be coordinated across marine and catchment management frameworks, linking climate adaptation with water quality, biodiversity conservation, and coastal zone management.

In the war-affected areas of the Black Sea, adaptation planning should also incorporate post-war environmental recovery and restoration. Rebuilding damaged coastal ecosystems, restoring environmental monitoring systems, and integrating climate resilience into recovery and reconstruction efforts will be important for strengthening the region's long-term adaptive capacity.

2.2. Catchment area effects

2.2.1 Projected impacts

The Black Sea is strongly influenced by processes occurring within its extensive catchment area, which covers nearly one-third of continental Europe and includes major river systems such as the Danube, Dniro, Dniester, Don, Southern Bug, etc. Climate change is expected to alter hydrological, ecological, and geomorphological processes throughout the basin, with significant consequences for the marine environment and coastal communities.³⁵

Changes in precipitation patterns are likely to increase seasonal variability across the catchment. Northern and central parts of the basin are expected to experience higher winter precipitation, while southern regions may face more frequent summer droughts and prolonged dry periods.³⁶ At the same time, more intense rainfall events may increase the risk of flooding, erosion and nutrient runoff from agricultural areas.

Changes in precipitation and temperature will also affect river discharge into the Black Sea. While projections of annual runoff vary between sub-basins, a general shift toward higher winter flows and lower summer flows is anticipated.³³ Such changes may alter sediment transport, nutrient loading, and freshwater inputs to coastal ecosystems, affecting salinity patterns, primary productivity, and eutrophication dynamics, particularly on the northwestern Black Sea shelf.

Cryospheric changes are also expected across the catchment. Rising temperatures are projected to reduce snow-cover duration and snow-water storage in mountainous regions such as the Carpathians and Caucasus, resulting in earlier spring snowmelt and changes in seasonal runoff patterns.³⁴

35 ICPDR. 2021. Climate Change Adaptation Strategy for the Danube River Basin. https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_climate_change_adaptation_strategy_web.pdf

36 European Environment Agency. (2024). European climate risk assessment (EEA Report No. 01/2024). Publications Office of the European Union. <https://doi.org/10.2800/8671471>

Coastal areas are particularly vulnerable to these changes. Sea-level rise, combined with increased storm intensity and changes in riverine sediment supply, is expected to accelerate coastal erosion, shoreline retreat, flooding, and saltwater intrusion in low-lying coastal areas, estuaries, lagoons, and deltas³⁷. These processes may threaten settlements, infrastructure, agricultural land, and valuable coastal habitats.

Climate change is also expected to affect terrestrial ecosystems throughout the catchment. Forests may experience increased drought stress, pest outbreaks and wildfires, as well as shifts in species composition, particularly in southern and eastern regions.^{38, 39} Wetlands, floodplains, and freshwater ecosystems may face reduced water availability and increased ecological degradation, reducing their capacity to provide essential ecosystem services such as water purification, flood regulation, and carbon storage.

These climate-related impacts will interact with existing pressures, including intensive agriculture, urbanisation, pollution, habitat fragmentation, and unsustainable water management, potentially increasing cumulative pressures on both freshwater and marine ecosystems.

2.2.2 Adaptation needs

Adaptation in the Black Sea catchment area requires an integrated river basin and ecosystem-based approach that strengthens resilience to climate change while addressing existing environmental pressures. Given the strong links between terrestrial, freshwater, and marine ecosystems, adaptation measures should be coordinated across sectors and administrative boundaries.⁴⁰ Improved water resource management will be critical to addressing increasing variability in precipitation and river flows. Measures may include strengthening drought management plans, improving water-use efficiency, enhancing water retention in landscapes, restoring natural floodplains, and promoting nature-based solutions that reduce flood risks while supporting biodiversity.

Reducing nutrient and pollution loads from agriculture, industry, and urban areas remains a key adaptation priority. Improved wastewater treatment, sustainable agricultural practices, better nutrient management and restoration of riparian buffer zones can strengthen ecosystem resilience while helping to reduce eutrophication in the Black Sea. Protecting and restoring wetlands, floodplains, forests, and other natural ecosys-

37 Ecoaction. (2019). Water is coming: Climate change and sea level rise in Ukraine. Ecoaction. <https://en.ecoaction.org.ua/wp-content/uploads/2019/04/water-is-coming-eng-short.pdf>

38 Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M. J., & Marchetti, M. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, 259(4), 698–709. <https://doi.org/10.1016/j.foreco.2009.09.023>

39 European Environment Agency. (2024). European climate risk assessment (EEA Report No. 01/2024). Publications Office of the European Union. <https://doi.org/10.2800/8671471>

40 ICPDR. 2021. Climate Change Adaptation Strategy for the Danube River Basin. https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_climate_change_adaptation_strategy_web.pdf

tems can further enhance climate resilience by improving water regulation, reducing erosion, storing carbon and supporting biodiversity. Particular attention should be given to conserving climate refugia and maintaining ecological connectivity, allowing species and ecosystems to adapt to changing environmental conditions.

Adaptation in coastal areas should include integrated coastal zone management, climate-resilient spatial planning, protection and restoration of coastal habitats, and measures to address sea-level rise, coastal erosion, and flooding. Nature-based solutions, such as restoring wetlands, dunes, and coastal vegetation, can provide multiple benefits for climate adaptation and biodiversity conservation.⁴¹

Strengthening monitoring, climate services, early warning systems, and transboundary cooperation across the Black Sea basin will be essential for effective adaptation planning. Given the transboundary nature of major river basins and marine ecosystems, cooperation among riparian and coastal states will be necessary to manage climate risks and support long-term ecosystem resilience.⁴²

In the northern part of the Black Sea, especially in the Ukrainian sector, adaptation efforts should be closely linked with post-war recovery and reconstruction. Rebuilding damaged water infrastructure, restoring degraded ecosystems, strengthening environmental monitoring systems and integrating climate resilience into recovery planning provide an opportunity to reduce future climate risks while advancing sustainable development and environmental restoration.⁴³

41 United Nations Environment Programme (2021). Adaptation Gap Report 2021: The gathering storm – Adapting to climate change in a post-pandemic world. Nairobi. <https://wedocs.unep.org/items/bba9a0ad-c213-48ef-b039-c1d3c240a3b8>

42 Black Sea Strategic Research and Innovation Agenda: Final edition. (2023). Horizon 2020 Programme of the European Union. https://connect2blacksea.org/wp-content/uploads/2024/01/Black-Sea-SRIA_2023.pdf

43 United Nations Environment Programme. (2023). Environmental assessment of the impacts of the war in Ukraine and prospects for a green recovery. United Nations Environment Programme. <https://www.unep.org/resources/report/environmental-assessment-impacts-war-ukraine-and-prospects-green-recovery>