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Ocean Acidification in the Baltic Sea

Report by Anu Vehmaa and Marko Reinikainen

Air Pollution & Climate Secretariat AirClim

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The report is also available in pdf format at www.airclim.org.

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Introduction – What is ocean acidification?

Climate change – caused by human activities – is a commonly known threat today. Burning of fossil fuels is releasing carbon into the atmosphere; carbon that has been buried in the ground for millions of years. In addition, changes in land use are altering the carbon cycle of the Earth. The ever-increasing **carbon dioxide (CO_2)** concentrations in the atmosphere result in global warming. However, a significant share of the CO_2 is taken up by surface oceans. Since the industrial revolution, approximately 30% of the extra CO_2 released into the atmosphere has ended up in the oceans. This buffering effect mitigates climate change but not without consequences for the life below water.

Dissolution of CO_2 in surface waters causes shifts in the acid-base equilibria of seawater in a process called **ocean acidification**. As a result, CO_2 and bicarbonate (HCO_3^-) concentrations in the water are increasing. The hydrogen ion (H^+) concentration also increases, which can be detected as decreasing pH. Conversely, the concentration of carbonate ions (CO_3^{2-}) decreases.

Ocean acidification is controlled by **total alkalinity** – the buffering capacity – of the water. The alkalinity of natural waters is described as an excess of bases over acids, and thus the ability of the water to neutralise the addition of acids (for example increasing CO_2 levels). The higher the alkalinity of the water, the smaller the change in pH when CO_2 dissolves in it, and the lower the alkalinity, the larger the change in pH.

The pH of surface seawater is typically around 8, which means that it is slightly basic (pH > 7). Ocean acidification shifts the pH towards neutral (pH = 7). Over the industrial era, the surface pH has dropped by 0.1 on the pH scale. Depending on future atmospheric CO_2 emissions and the model used, the surface ocean pH is projected to drop to 8.05 – 7.75 by the end of the 21st century. Although the changes on pH scale seem small, they correspond to an increase in oceanic acidity (H^+) of up to 200%.

Changes in aquatic living conditions have an impact on the performance of organisms. Calcifying plants and animals in particular are under threat because a decrease in pH impairs the **calcification process**. A reduction in the saturation state (Ω) of calcium carbonate ($CaCO_3$) in both its mineral forms – aragonite and calcite – can have negative impacts on the calcification rates of several marine taxa. For example, researchers have observed increasing deterioration of coral structures, and calcifying plankton, as well as thinning of the shells of mussels and oysters. The saturation state expresses the thermo-dynamic tendency for $CaCO_3$ to form or to dissolve. Saturation state values above one ($\Omega > 1$) indicate oversaturation, and values below one ($\Omega < 1$) indicate undersaturation. Exoskeleton dissolution of some bivalve and gastropod species happens when the saturation state is well below one ($\Omega << 1$). Although this rarely occurs in surface oceans, it is a more common phenomenon in temperate coastal upwelling areas. Upwelling events bring hypoxic deep water with high CO_2 concentrations closer to the surface, which leads to a decrease in the saturation state and less-hospitable conditions for $CaCO_3$ dependent organisms.

Acidification can also induce other physiological maintenance costs, which can in particular be reflected in growth and survival in the early stages of life. Furthermore, acidification can alter fish behaviour and learning by impairing their sensory mechanisms, hearing, olfaction and vision. While acidification can have negative effects on some species, others may benefit from it. Possible benefiters include macroalgae, due to improved carbon availability. Whatever the case, ocean acidification modifies food webs and, eventually, ecosystem functions in general.

The Baltic Sea – a unique case in so many ways

The Baltic Sea is especially vulnerable to ocean acidification because of its low total alkalinity. Low alkalinity combined with high primary production and respiration, and the resulting high remineralisation of organic matter, are the causes of notable diurnal and seasonal fluctuations in the pH of surface waters.

The Baltic Sea (Fig. 1) is one of the largest brackish water bodies in the world. It has a surface area of 420,000 km^2 but its average depth is only 54 m, and one third of its area is less than 30 m deep. The small water volume and slow turnover rate of water make the sea especially vulnerable to the pressures placed on it by the 85 million people who live in the catchment area. The Baltic Sea is characterized by steep salinity and temperature gradients. The most northern parts are almost freshwater (salinity < 3) and are covered with ice in winter. In the south, the climate is milder and salinity is closer to that of seawater (~15 in the Kattegat). In addition to the north-south salinity and temperature gradients, permanent vertical stratification restricts vertical water movements in most parts of the sea.

The Baltic Sea is considered to be especially vulnerable to ocean acidification because its alkalinity is lower than that of the oceans. Due to the generally low total alkalinity, high primary production and resulting high remineralisation, the pH of its surface waters is less stable than in the oceans. During the growing season, CO_2 is taken up through intensive photosynthesis, and this raises the pH during the daytime. During the night and in areas below the photic zone, however, respiration releases CO_2 back into the water, thus lowering the pH. Daily fluctuations in seawater pH at a local scale can be as high as 1.2 (inside a *Fucus* belt, Wahl and co-workers 2018), with the most intense fluctuations occurring near macroalgal and seagrass beds, as well as in phytoplankton blooms. In winter, primary production is reduced due to low temperature and lack of light, while remineralisation of organic matter produces CO_2 and decreases pH in deep water. Mixing processes bring the CO_2-enriched water to surface, which results in minimum pH values in winter in surface waters.

Increased atmospheric CO_2 and the resulting acidification is not the only factor influencing the future pH balance of surface water in the Baltic Sea, but in terms of total alkalinity (see Info box) it is by far the most significant factor. Progressive eutrophication due to increasing nutrient load will not inhibit acidification, but will amplify the seasonal fluctuation by increasing production and mineralisation. Changes in temperature and salinity will only have a minor effect on pH balance. In addition, acid precipitation, as well as the increase in river transport of dissolved organic matter, will only have a marginal acidification effect, even though 20–30% of the dissolved organic carbon entering the Baltic Sea is bioavailable and can be respired, which releases CO_2. Furthermore, mineralisation of dissolved organic carbon into inorganic carbon may increase acidification in coastal areas, and the ocean acidification effect is intensified in coastal areas suffering from upwellings of CO_2-enriched deep water. Whereas changes in atmospheric CO_2 are reflected in surface water pH within a month, response times for changes in alkalinity and runoff are on the order of decades, due to the long residence time in water.

Figure 1. The catchment area, the sub-basins, and the seven largest rivers draining into the Baltic Sea. (Data: HELCOM; CCM River and Catchment Database © European Commission – JRC, 2007; Vogt, J.V. et al. (2007): A pan-European River and Catchment Database. European Commission – JRC, Luxembourg, (EUR 22920 EN) 120 pp.)

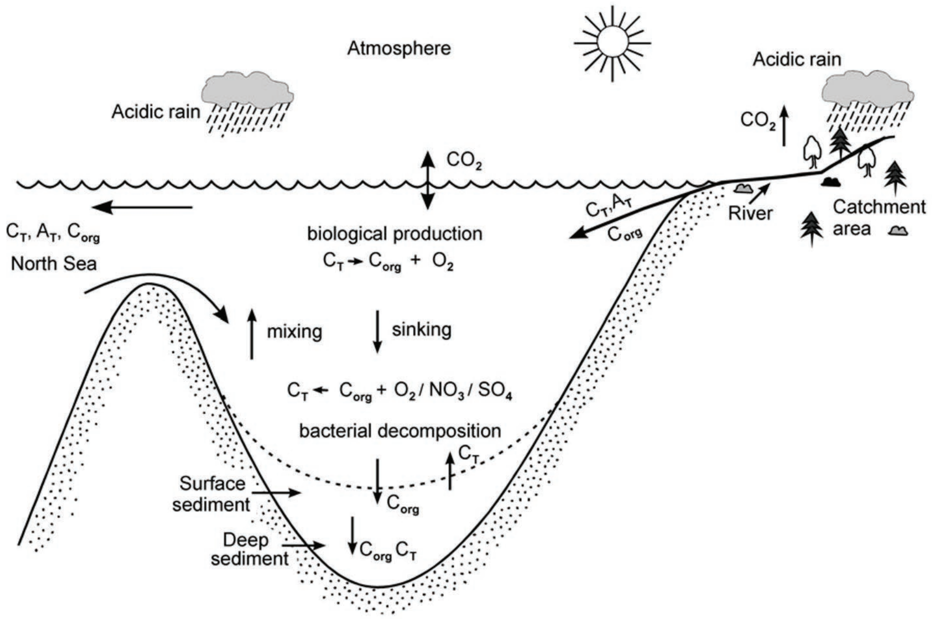


Figure 2. *Schematic of the Baltic Sea carbon cycle: C_{org}, organic carbon; C_T, total inorganic carbon; A_T, total alkalinity; CO_2, carbon dioxide; O_2, oxygen; NO_3, nitrate; SO_4, sulphate (from Omstedt, A., Humborg, C., Pempkowiak, J. Perttilä, M., Rutgersson, A., Schneider, B., Smith, B. (2014) Biogeochemical Control of the Coupled CO_2–O_2 System of the Baltic Sea: A Review of the Results of Baltic-C. AMBIO 43, 49–59. https://doi.org/10.1007/s13280-013-0485-4)*

Total alkalinity – the buffering capacity of the Baltic Sea

Unlike in the oceans where alkalinity is relatively constant, the total alkalinity of the Baltic Sea varies depending on the area, because it is mostly controlled by the total alkalinity of the inflowing rivers and North Sea water. The total alkalinity of river water in turn depends on the weathering properties and composition of the bedrock in the catchment area (Fig. 2). In the northern parts of the Baltic catchment, the bedrock is formed of granite, which produces less alkalinity than limestone as a result of weathering. The bedrock of the southern parts consists of clay, limestone and sandstone, which in turn produces higher alkalinity. The river water in the south therefore has higher alkalinity than the river water in the north. Furthermore, the inflowing high-salinity seawater from the North Sea has high alkalinity, which results in a positive linear relationship between salinity and alkalinity in the Gulf of Finland and in the Gulf of Bothnia. The Gulf of Riga is an exception, since the limestone bedrock makes the inflowing river water even more alkaline than open ocean water. The Baltic Proper is a mixing area for waters entering the Baltic Sea, and the linear salinityalkalinity relationship is less pronounced here.

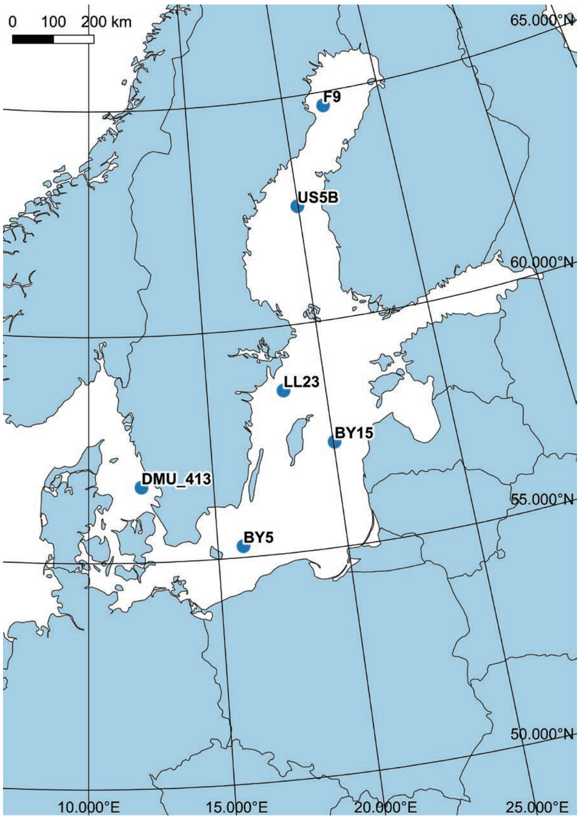
Increasing atmospheric CO_2 concentration enhances soil weathering, thus increasing the alkalinity of the river water entering the sea. Increasing atmospheric CO_2 and climate warming both have a positive impact on terrestrial plant growth and soil respiration, and the resulting increase in soil CO_2 accelerates mineral weathering.

Climate change is projected to increase precipitation, especially in the northern areas of the Baltic Sea catchment, whereas the southern regions are expected to become drier. Although increasing rainfall dilutes the alkalinity of the inflowing river water, the overall effect is positive; the alkalinity flux increases due to increased discharge.

Another external source of total alkalinity is submarine groundwater discharge. As with river water, the alkalinity of groundwater depends to some extent on the geological properties of the catchment area. The significance of groundwater discharge on the total alkalinity budget is still unknown, however, it likely has at least local importance.

In addition to external total alkalinity sources, internal total alkalinity generation enhances the buffering capacity of coastal oceans. Primary production, aerobic mineralisation (including nitrification), denitrification, and sulphate reduction and oxidation all affect total alkalinity. Primary production and aerobic mineralisation in the water column increase alkalinity, whereas aerobic mineralisation in surface sediments decreases it. Denitrification, both in the water column and in the sediments, has a positive effect on alkalinity. The net effect of sulphate reduction and sulphide oxidation on alkalinity is also positive if sulphur is buried permanently, in the form of pyrite for example. However, this effect is smaller than the effect of denitrification. Increased eutrophication-derived sedimentation and mineralisation of particulate carbon reduces the oxygen concentration in the water column and increases the alkalinity generation in the sediments.

The total alkalinity of the surface water has increased in the Baltic Sea over recent decades (Fig. 3). Both internal and external drivers have been proposed to explain this trend. According to German researchers, the observed rates of change have been the highest in the low-salinity northern parts and decrease gradually with increasing salinity towards the south. The researchers have calculated that the increase in total alkalinity has compensated for almost half of the CO_2-induced acidification in the central Baltic Sea and almost 100% in the Gulf of Bothnia. Nevertheless, they warn that the increasing alkalinity should not be interpreted as protection against future CO_2-induced acidification.



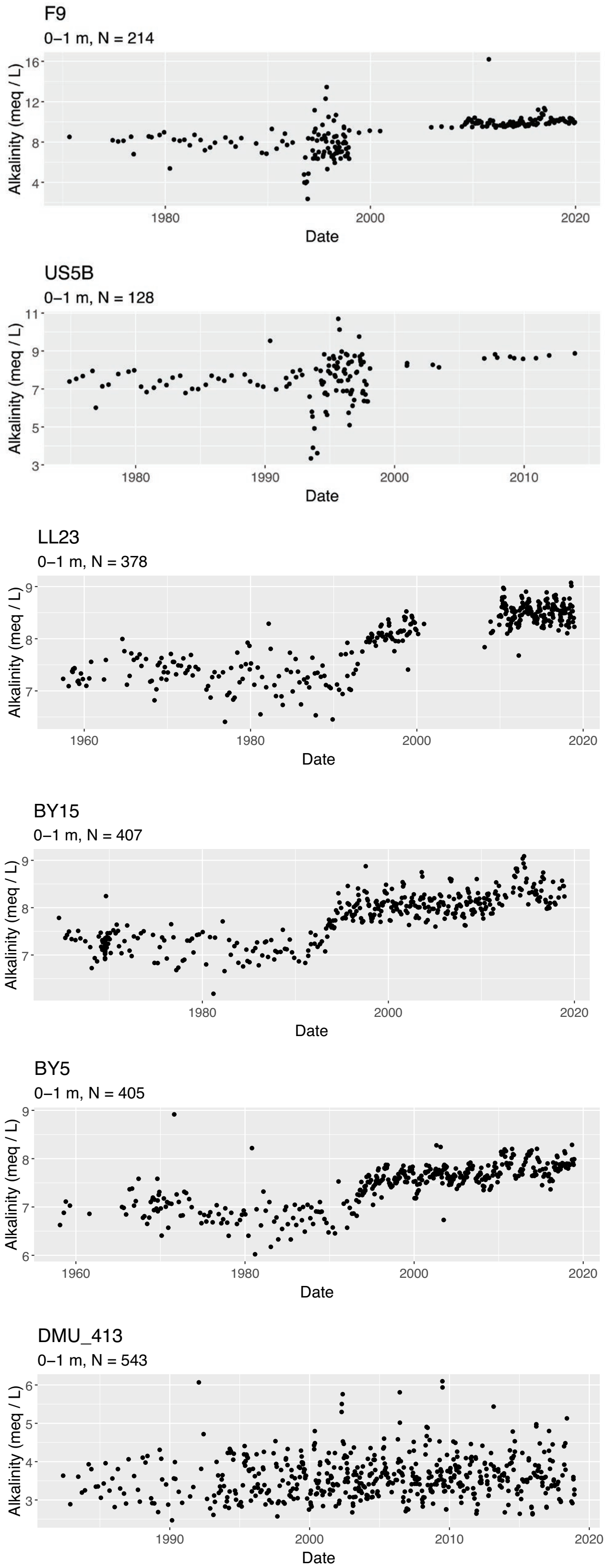


Figure 3. *Time series of surface water (0–1 m) total alkalinity normalised to a salinity of 35 across the Baltic Sea. The graphs show increasing trends over the past few decades. The data collected before 1995 includes larger uncertainties compared to the present, due to the lower accuracy of the measurements (Data: HELCOM, ICES Dataset on Ocean Hydrography, The International Council for the Exploration of the Sea, Copenhagen. 2014)*

Effects on the Baltic Sea ecosystem

Ocean acidification is yet another encumbrance in a long list of burdens that the Baltic Sea ecosystem is forced to endure. Information on acidification effects is slowly accumulating. Not surprisingly, the effects are widely dependent on other environmental stressors, because of interactions, for example, with eutrophication. So far, the studies have indicated that acidification has negative effects on, for example, blue mussel larvae, benthic bivalve Limecola, heterotrophic bacterioplankton, and western Baltic cod larvae.

Due to its low salinity and young geological age, the Baltic Sea ecosystem has a low number of species. However, biodiversity is greater than might be expected under such conditions due to the unique salinity gradients and versatile habitats.

The effects of ocean acidification on living organisms have mostly been studied at the species level, whereas evidence on community responses has only begun to accumulate in recent years. The direction and scale of the acidification effects are also largely dependent on other drivers, such as warming, salinity changes, light and eutrophication. In this section, the effect of ocean acidification on the Baltic Sea underwater communities is summarised using contemporary scientific results for the keystone/foundation species.

Coastal zone

The coastal zone is a more unstable habitat than the pelagic or benthic areas. It is subjected to seasonal changes, wave action and is also influenced more by human activities. Coastal areas are therefore especially vulnerable to anthropogenically induced environmental changes. At the same time, the most diverse communities are found in the coastal zone.

Bladderwrack

Brown macro-algae, bladderwracks (*Fucus vesiculosus, F. radicans*) are foundation species of littoral communities. On rocky shores, perennial bladderwracks provide habitat and food for numerous species throughout the year. The Baltic bladderwracks are sensitive to eutrophication, thus their occurrence has decreased during recent decades. However, macroalgae are expected to benefit from ocean acidification because enhanced CO_2 availability could saturate their carbon demand during photosynthesis and save energy when carbon-concentrating mechanisms can be downregulated.

The effects of ocean acidification on Baltic Sea bladderwrack populations have been studied in combination with other environmental variables. All in all, according to experiments using populations from the southern Baltic (Kiel Fjord) and the northern Baltic (Gulf of Finland), the effects seem minor. Ocean acidification may have slightly positive effects on growth, in the form of increased carbon availability and storage, but the response depends on the season and day length, and is small in comparison to other environmental effects such as irradiance and warming.

Regardless, the future seems challenging for the bladderwrack. Summer heatwaves in particular have proven detrimental. Climate warming, decreasing salinity, and coastal eutrophication all favour fast-growing filamentous green algae, epiphytes and phytoplankton over bladderwrack. Thus, the ecosystem functions that these perennial species provide are threatened. Local or regional actions, such as alleviation of overfishing and eutrophication may mitigate the ongoing loss of bladderwrack.

Blue mussel

Blue mussel (*Mytilus edulis trossulus* complex) is a keystone species in the Baltic Sea ecosystem. It is an efficient filter feeder and, in the process, transfers nutrients and organic matter from the pelagic to the benthos. Thus, it is an important link between the two habitats. Furthermore, blue mussels act as ecosystem engineers by creating complex structures for many organisms and are the main food source for several fish and bird species.

Bivalves are dependent on their protective shells and, as calcifying organisms, they are especially vulnerable to ocean acidification. According to recent studies using Baltic populations, the benthic life stage is able to compensate for the costs of acidification when food is abundant. The larval stages are less fortunate due to the high calcification rates required during the formation of the first larval shell and the limited energy provided by the egg. Calcification is energetically costly for the Baltic Sea blue mussel, and the costs increase with decreasing salinity. Recently it has been suggested that reduced growth and the resulting small size of Baltic Sea blue mussels is a consequence of high calcification costs instead of low salinity-derived osmotic stress. Projected acidification, resulting in a decreasing $CaCO_3$ saturation state, and desalination might thus set a severe constraint on the future blue mussels.

Baltic Sea blue mussel populations have adapted to the fluctuating pH conditions and low alkalinity. In a common garden experiment, larval development of a North Sea population and a Baltic population originating from the CO_2-enriched habitat (Kiel Fjord) were tested under elevated CO_2 conditions. Both populations showed impaired larval development, but the effect was less severe for the Baltic population: shell length reduction was smaller and the survival rate was higher at elevated CO_2 when compared to control conditions. Fluctuating environments, such as in the Kiel Fjord, facilitate the maintenance of high genetic diversity, which became apparent in multigenerational experiments comparing CO_2-sensitive and CO_2-tolerant blue mussel families. The experiment revealed a heritable component of calcification performance in early larval development. Baltic Sea blue mussels may thus have the potential to adapt to the effects of ocean acidification. In addition, blue mussels can improve their calcification rates in acidified conditions by settling in a dense macroalgal or seagrass habitat, which can offer a temporal refuge from acidification stress. In experimental conditions, *M. edulis* has been able to maintain most of its calcification activity by shifting it into the daytime, when the photosynthetic activity of bladderwrack increases the mean pH of the habitat.

Open Sea

Plankton ecosystems

Plankton communities form the foundation of pelagic productivity. Primary production performed by phytoplankton and bacteria is transferred through zooplankton grazers and the microbial loop for use by plankton-eating fish, and eventually predatory fish, marine mammals and sea birds.

There seems to be large variability in tolerance to ocean acidification between and within phytoplankton species, which makes it difficult to draw any general conclusions. Mesocosm experiments in the western Baltic Sea (Kiel Fjord) and the northern Baltic Sea (Gulf of Finland), and a microcosm experiment in the Baltic Proper (Askö laboratory) have shown that, at the ecosystem level, there are some general effects. Firstly, primary production, measured as phytoplankton biomass or as chlorophyll a concentration, is positively affected by ocean acidification. The increased production is caused by the rarer and smaller pico-sized species, while the dominating species appear unaffected. Secondly, acidification has an enlarging effect on both phytoplankton and cyanobacteria cell size. Thirdly, heterotrophic bacteria are negatively impacted. The effects of ocean acidification on phytoplankton are counteracted by the even stronger effect of warming, which decreases primary production and cell size. By contrast, warming and acidification seem to have synergistic effects on bacterioplankton community dynamics, which are also sensitive to changes in salinity and dissolved organic carbon.

Due to their important role in marine systems, calanoid copepods are the most widely studied zooplankton taxa in ocean acidification research. In the Baltic Sea, the reproductive success of the species *Acartia sp.* and *Eurytemora affinis* has been tested. Of the two species, Eurytemora seems to be more tolerant to acidification, possibly due to greater exposure and adaptation to wider pH variations due to stronger diel vertical migration as adults. *Acartia* seems to be able to cope with acidification partly by changing its size and by adjusting its offspring to the environment. This plasticity might buffer short-term negative effects of acidification, and buy time for genetic adaptation, which is a potential adaptation strategy for species with short generation times within the time frame of the ongoing environmental changes.

Plankton ecosystems are complex, and it is important to realise that seasons, trophic interactions, and the geographical region where the experiments are conducted are all factors that influence the results of acidification studies when natural plankton communities are used. Furthermore, even different functional traits within a species may give opposite responses. For example, in a mesocosm experiment testing the interaction of end-of-century global warming and ocean acidification effects on the calanoid copepod *A. tonsa*, acidification increased mortality at higher temperatures but decreased it at lower temperatures, while size and growth were, perhaps surprisingly, positively affected by acidification.

The evidence is still scarce, but it is probable that the shift to smaller-sized phytoplankton and the increasing importance of the microbial loop will favour zooplankton grazers that are able to consume bacteria. This increase in regenerative primary production will diminish energy transfer to higher trophic levels, but also decrease the flow of organic matter that feeds the benthic ecosystem. Therefore, the functions that the pelagic ecosystem provides are endangered.

Benthic ecosystems

Because Baltic Sea benthic communities are species poor, their functionality is dependent on a few key species. The communities are especially vulnerable to ocean acidification because many of the benthic species are calcifying organisms. In addition, they are already suffering from widespread hypoxia/anoxia, and the related low $CaCO_3$ saturation state.

The bivalve *Limecola balthica* (formerly known as *Macoma balthica*) is an abundant species throughout the soft-bottom areas of the Baltic Sea, and it is one of the dominant species in the species-poor northern Baltic. *Limecola* is a bioturbator. By burrowing into the sediments, it enhances oxygenation of the sediment layers and recycling of organic matter, thus contributing to the overall functioning of the benthic ecosystem. Ocean acidification negatively affects *Limecola*. Experiments using a population from the Gulf of Finland have shown that even a small decrease in pH slows down the growth rate of free-swimming larvae, as well as delaying their development and decreasing survival. Slower larval growth and development, and the associated delayed settling of the post-larvae increase the predation risk by prolonging the time spent as unprotected larvae in plankton. After settling to the sediment, the juvenile and adult *Limecola* are subjected to possible low-oxygen conditions and concomitant decreased pH. According to experiments done in the Gulf of Finland and the Gulf of Gdansk, they are less vulnerable to lower pH than the larval stages. However, maintenance of basic metabolism, regulation of internal pH balance or changes in their burrowing behaviour may have negative effects on their energy budget and could be reflected in their reproductive success and overall population development.

Even though seasonal fluctuations in seawater pH might facilitate evolutionary adaptation to acidification, *Limecola* larvae in the Baltic Sea (Gulf of Finland) seem to be more vulnerable to the combined stress of warming and acidification than larvae that originate from populations in the Bay of Biscay or southern North Sea. Thus, Baltic Sea populations of this keystone benthic species are threatened due to the combined stress of acidification, hypoxia and warming.

Pelagic fish

The effects of ocean acidification on Baltic Sea fish populations have not yet been widely studied. One of the few species that has gained attention is the Atlantic cod (*Gadus morhua*). Cod is the top predator in the pelagic food webs. By preying upon planktivorous fish, sprat and herring, it ensures high zooplankton abundance which, in turn, limits phytoplankton blooms through intensive grazing. Thus, changes in the top-down control provided by cod can have cascading effects on the whole ecosystem.

Like many other commercial fish stocks in the world, the two separate cods stocks (eastern and western) in the Baltic Sea have both decreased dramatically during recent decades. In addition to overfishing, cod have suffered from eutrophication related hypoxia and decreased salinity. The status of the eastern Baltic cod stock is especially poor at present. The fish have low growth rates, are in poor condition and suffer high mortality. The reasons driving this situation are unclear.

The eastern Baltic cod stock may be less vulnerable to ocean acidification than the western stock. Laboratory experiments using projected end-of-the-century and beyond acidification parameters found no effect on the sperm behaviour, egg hatching, larval development or larval otolith size of eastern cod. However, an experiment applied to western cod resulted in a doubling of the larval daily mortality at end-of-the-century acidification levels compared to the present day CO_2 concentrations. The increase in larval mortality could lead to a considerable decrease in recruitment. More studies are needed to confirm these results. In addition, it would be valuable to know how the two most important prey species of cod, the Baltic herring and sprat, are reacting to ocean acidification.

Mitigation and adaptation

The main remedy for ocean acidification is to cut emissions of CO_2. Meanwhile, ecosystem resilience to acidification could be improved through actions that maintain biodiversity, by freeing the ecosystems from other environmental stressors. Because our knowledge on the acidification effects on the Baltic Sea ecosystem is still deficient, more research is needed before acidification adaptation can be incorporated into more specific management plans.

In a global perspective, ocean acidification is recognised as a major challenge. For instance, it is considered in the United Nations' 2030 Agenda for Sustainable Development and the associated Sustainable Development Goals (SDG). The SDG 14, "Life below Water", targets enhancing conservation and sustainable use of the oceans, seas and marine resources. Specifically, within this SDG, target 14.3 aims to minimise and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels. The associated indicator, 14.3.1, requires the measurement of average marine acidity (pH) at an agreed suite of representative sampling stations.

Ultimately, the mitigation of ocean acidification to meet SDG target 14.3 requires cutting emissions of CO_2 from the burning of fossil fuels, and at present, mitigation is largely addressed through the same global agreements that concern greenhouse gases in general, such as the Paris Agreement. Nationally, this should translate into the application of sufficient national mitigation measures. For EU members, the harmonisation of the national measures with the relevant EU directives and other regulatory instruments is also required, including upcoming instruments related, for example, to the European Green Deal.

With regards to governance, however, ocean acidification also needs to be recognised in its own right, and according to a recent article by Galdies and co-workers (2020) "The problems associated with and the solutions needed to address OA [ocean acidification] are unique and cannot be bundled together with traditional climate change responses and measures". An approach that recognises ocean acidification specifically is required, for instance, because the geographic distribution of ocean acidification is highly variable (as described in earlier sections), and because adaptation measures that recognise unavoidable ocean acidification are needed.

Adaptation measures for ocean acidification can be found within the realms of conservation or restoration of biodiversity. Such measures may improve resilience against disturbance in general, and measures to decrease the overall anthropogenic pressures on biodiversity could in the short term also increase resilience to ocean acidification.

In theory, several instruments are already in place to protect marine ecosystems in Europe, including in the Baltic Sea. For instance, the Marine Strategy Framework Directive (MSFD) could guide EU member states to a coordinated view on marine protection in general, and specifically also regarding ocean acidification. The Baltic Sea Action Plan of HELCOM furthermore provides a framework, particularly for the Baltic Sea, that also extends to nations outside the EU. HELCOM's Marine Protected Areas (MPAs) are an existing network of marine areas with protection aims, including the protection of biodiversity.

The inclusion of an area into these MPAs does not automatically guarantee a specific level of protection, as the protection measures require national legislation for their implementation. Nevertheless, these MPAs provide a backbone for coherent protection of biodiversity that could also increase resilience to ocean acidification. Initiatives by local stakeholders, including those of municipalities and even private property owners, can be found within these MPAs, and some of the MPAs are based on regional initiatives to join UNESCO's "World Network of Biosphere Reserves" and other international programmes.

Nevertheless, even if there are instruments to meet mitigation, adaptation and protection needs both within the EU in general, and specifically for the Baltic Sea, there seems to be a lack of measures that target ocean acidification explicitly.

Returning to the above citation by Galdies and co-workers regarding the recognition of ocean acidification in its own right, rather than "bundled together" with (other) climate change measures, the authors concluded that "EU-wide actions remain still incomprehensible and uncoordinated", even if ocean acidification is included in overarching policy documents such as the SDGs. As for the MSFD, and its national implementations, the authors pointed out that "…national policies rarely emphasised the overarching element of the Marine Strategy Framework Directive (MSFD)" in general, and that the MSFD does not include monitoring descriptors that concern ocean acidification specifically.

This is not a trivial issue. Even if the abatement of climate change and the abatement of OA both require the mitigation of CO_2, the effects of temperature rise (and associated effects) and acidification are not the same. (Although they do occur concurrently and there can be interactions.)

As we have pointed out here, the protection of ecosystems from other stressors in the Baltic Sea could also provide synergies with regards to ocean acidification. Nevertheless, protection measures that also take ocean acidification into account specifically could provide explicitly tailored solutions, such as MPAs that are allocated appropriately. Although there is a lack of studies that can provide a basis for the designation of such refugia, there are some indications on useful approaches. For instance, protecting macrophyte beds (macroalgae and seagrass) can offer a temporal refuge for calcifying organisms. Such local or regional actions should of course not happen in isolation, but rather in tandem with other actions, such as alleviation of overfishing and eutrophication, to mitigate the ongoing loss of bladderwrack and other macrophytes, and at the same taking into account the need to increase resilience to ocean acidification.

Apart from pointing towards the need for policy makers to take science governance action against the ocean acidification issue in the Baltic Sea, we believe it is also important to find ways to efficiently communicate this issue to the general public, including the younger generation. In separate publications within this project, we have, for instance, highlighted the engagement of school children in citizen science through their participation in pH measurements (Fig. 4).

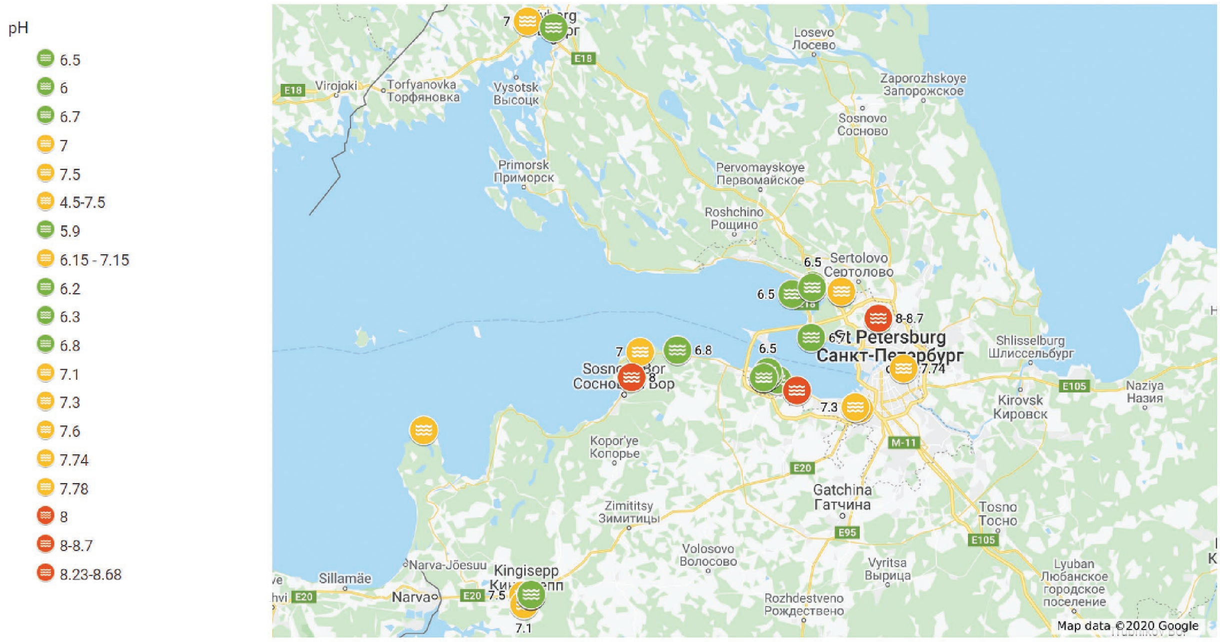


__Figure 4.__ Water quality in the rivers and coastal areas of the Saint Petersburg region has been monitored for several years by public observers of the NGO Friends of the Baltic, under the River Watch programme of the Coalition Clean Baltic. In 2016–2020 the River Watch groups, including school children, monitored pH levels. (From the BALSAM Country Report of Russia.)

Monitoring of acidification indicators

Water quality in the Baltic Sea has been monitored systematically for four decades, however monitoring of acidification indicators is still incomplete. Proper monitoring methods and indicators as well as sufficient seasonal sampling resolution are of vital importance for the understanding of ocean acidification.

Because of the complexity of the Baltic Sea CO_2 system, meaningful monitoring of ocean acidification must be both spatially and temporally frequent, as well as based on highly accurate and precise measurements. Furthermore, SDG 14 and the associated indicator 14.3.1 require the measurement of average marine acidity (pH) at an agreed suite of representative sampling stations.

Coordinated monitoring of Baltic Sea water pH started in 1979, however some data is available from as early as 1891. Today, monitoring is coordinated by the Baltic Marine Environment Protection Commission – also known as the Helsinki Commission (HELCOM) and the HELCOM COMBINE programme. The aims of the programme are 1) to identify and quantify the effects of anthropogenic discharges/activities in the Baltic Sea and in the context of the natural variations in the system, and 2) to identify and quantify the changes in the environment as a result of regulatory actions. Monitoring responsibilities for the Baltic Sea sub-areas are divided between the coastal states and their governmental institutes.

Baltic Proper: Estonia (Estonian Marine Institute), Finland (Finnish Environment Institute), Germany (Federal Research Institute for Rural Areas, Forestry and Fisheries), Latvia (Latvian Institute of Aquatic Ecology), Lithuania (Marine Research Centre), Poland (Institute of Meteorology and Water Management), Sweden (Swedish Agency Marine and Water Management) and Russia (State Oceanographic Institute)

Gulf of Bothnia: Finland and Sweden

Gulf of Finland: Estonia, Finland and Russia

Gulf of Riga: Estonia and Latvia

Gulf of Gdansk: Poland and Russia

Sound and the Kattegat: Denmark (Danish Centre for Environment and Energy) and Sweden

Great Belt: Denmark

Bay of Kiel and Bay of Mecklenburg: Germany

The monitoring data is accessible to everyone and can be downloaded using the HELCOM (*https://helcom.fi/baltic-sea-trends/data-maps/databases/)* or ICES databases (*https://www.ices.dk/data/dataset-collections/Pages/HELCOM.aspx*).

When studying the carbonate buffering system of sea water, four variables can be measured (total alkalinity, pH, dissolved organic carbon and partial pressure of CO_2). If two variables are determined accurately, it is theoretically possible to calculate the others. However, the calculations do not take into account the high concentrations of humic matter and other dissolved organic carbon in the Baltic Sea, and can result in erroneous total alkalinity values. The pH parameter is included in the COMBINE monitoring programme as one of the main parameters, meaning that it is measured on a regular basis (Fig. 5). For the parameters total alkalinity (Fig. 5) and pCO_2 there is only partial national monitoring at present. Development of more comprehensive acidification monitoring is in progress, and will be in place by 2024.

In addition to the COMBINE monitoring programme, Baltic countries conduct some water quality monitoring in their territorial waters (see the BALSAM Country Report of Russia). This data can possibly be helpful when estimating the state of the carbonate buffering system outside the COMBINE monitoring grid.

Monitoring of pH is based on potentiometric or spectrophotometric detection. Potentiometric detection (NBS pH scale) is more widely used because it is fast and simple, and it does not require any advanced or expensive equipment. Spectrophotometric detection is more accurate and more precise, but the equipment is more expensive. Temperature is measured and recorded simultaneously with pH. Total alkalinity is determined by potentiometric titration. Samples for pH and total alkalinity measurements are collected at depths of 1, 5, 10, 15, 20, 25 (Kattegat and the Belt Sea only), 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200, 225, 250, 300 and 400 metres; and as close to the bottom as possible.

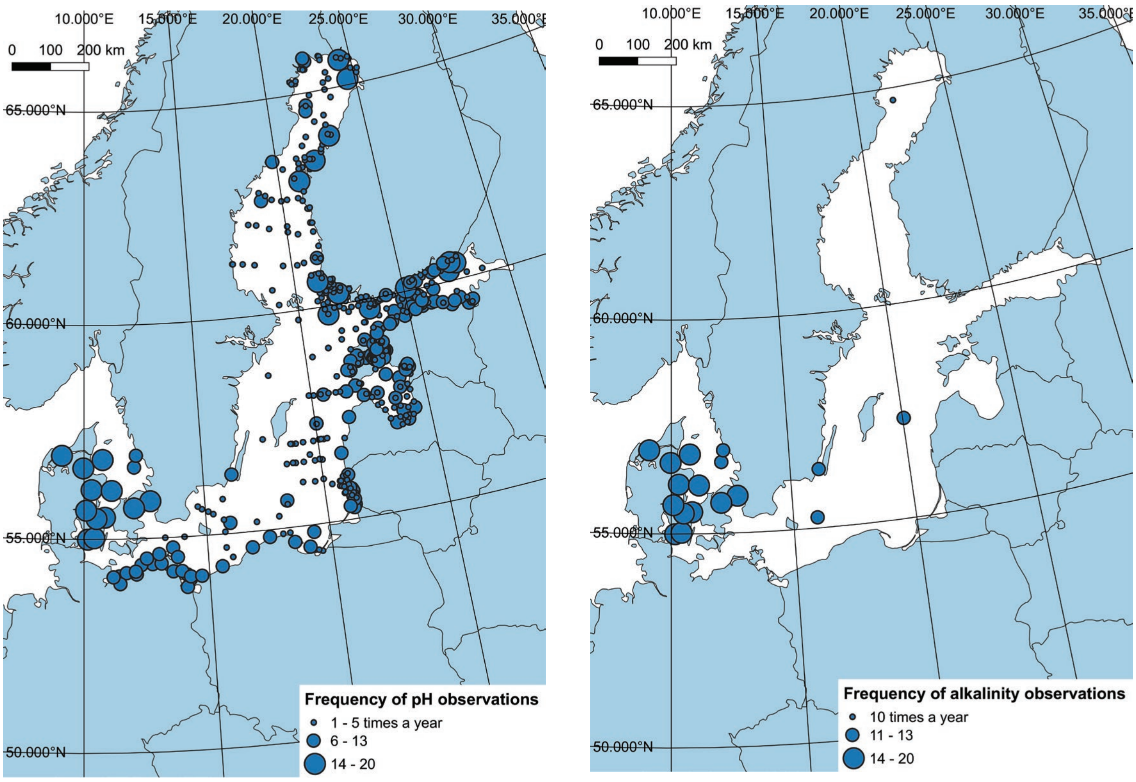


Figure 5. *Monitoring stations that are included in the HELCOM COMBINE programme, and the sampling frequency for pH and total alkalinity. (Data: HELCOM)*

The current state of acidification in the Baltic Sea

Decreasing pH trends can already be observed seasonally in some parts of the Baltic Sea. However, the quality of long-term data is partly questionable, which complicates the detection of trends. Modelling studies project that seasonal fluctuations in surface water pH will increase further, and that the main driver controlling the magnitude and direction of the future pH trends is the atmospheric CO_2 concentration.

The pH of Baltic Sea water has already been monitored for several decades, and the widest data sets include over a thousand observations (Fig. 6). Nevertheless, it is not easy to detect significant ocean acidification trends because measuring the pH of the Baltic Sea water is challenging, and the quality of the pH data is therefore partly questionable. The monitoring schedules, the equipment used, and the accuracy of the measurements have been changing over the years, which further complicates the analyses. Moreover, both seasonal and yearly variations and upwelling events may mask the long-term trends (Fig. 7), and the increase in total alkalinity (Fig. 3) has compensated in part for the CO_2-induced acidification.

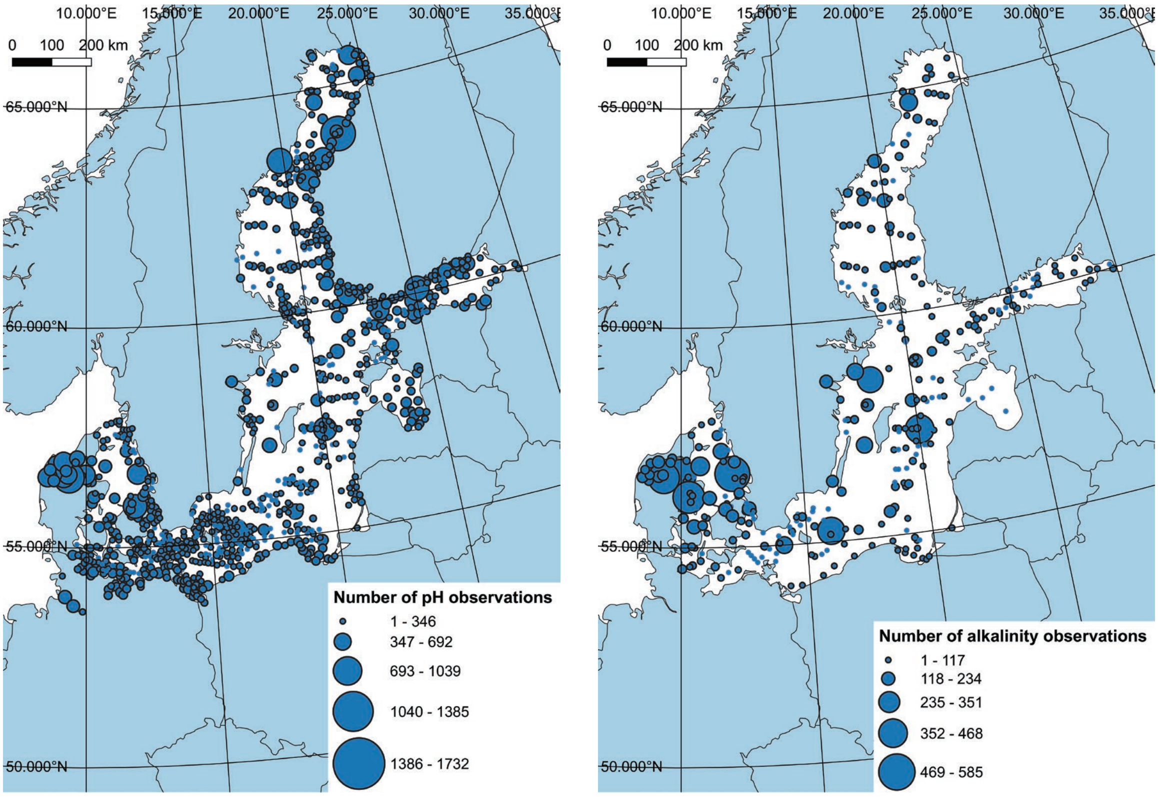


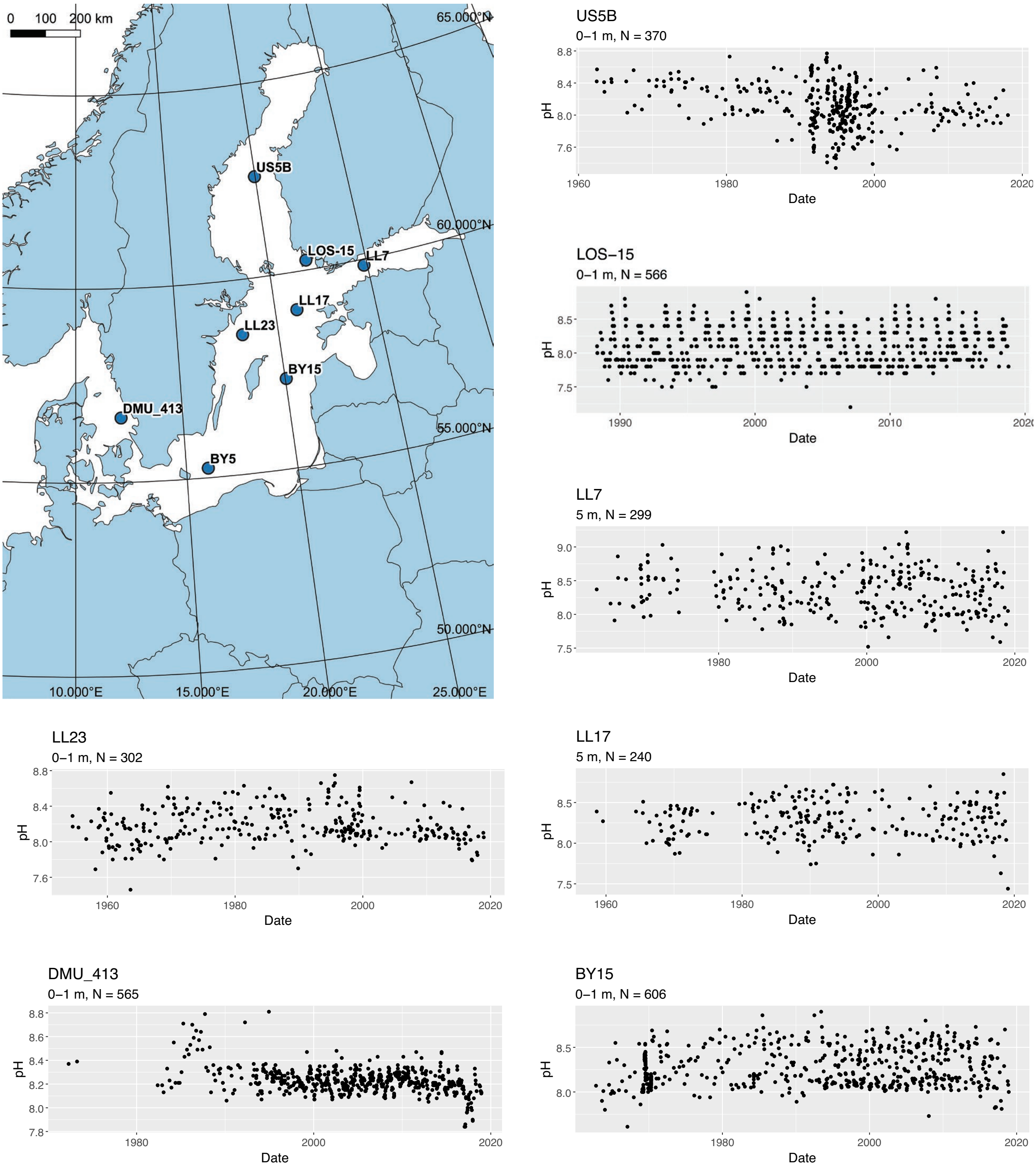
Figure 6. *Number of surface water pH and total alkalinity observations across the Baltic Sea. (Data: HELCOM, ICES Dataset on Ocean Hydrography, the International Council for the Exploration of the Sea, Copenhagen. 2014)*

In addition to acidification resulting from the atmospheric CO_2 increase, long-term pH monitoring data also reveals changes in primary production. For example, a draw-down of CO_2 and the resulting increase in maximum pH is evident in the surface water during the productive season in nutrientrich areas. In winter, surface water pH is more stable and at its lowest level, so it is easier to observe long-term trends in winter data.

Despite the difficulties in detecting long-term pH trends, there are a few studies reporting significant changes in the Gulf of Finland (e.g. from monitoring station LL7). Wintertime surface and deep-water pH has decreased there significantly between 1972 and 2009 and between 1979 and 2015 (Almén and co-workers 2017). The decrease has been sharper in deep water (0.008 units/year) than in surface water (0.003–0.006 units/year), possibly because of increased decomposition and CO_2 production caused by eutrophication. Recent modelling studies have projected the same phenomena: climate change and increasing nutrient loads will affect acidification mainly by modifying seasonal cycles (summer maximum and winter minimum), and deep-water conditions. According to these studies, the main driver controlling the magnitude and direction of the future pH trends is, however, the atmospheric CO_2 concentration.

The $CaCO_3$ saturation state will decrease along with the decreasing pH, which can impair calcification. The saturation state follows the alkalinity gradients, with the Bothnian Bay and the Gulf of Riga being at the opposite endpoints. Saturation states vary also seasonally, and the lowest values are found in late winter. In winter, surface waters of the Baltic Proper are already undersaturated with respect to aragonite ($\Omega < 1$) and almost undersaturated with respect to calcite ($\Omega = \sim 1$) (Tyrrel and co-workers 2008). In the Bothnian Bay, the wintertime saturation state of calcite is really low ($\Omega = 0.2$), whereas in the Gulf of Riga calcite remains oversaturated throughout the year (lowest values in March, $\Omega = 1.3$).

Highly productive coastal habitats that are suffering from seasonal hypoxia are already experiencing lower pH values and $CaCO_3$ saturation states than projected for the next centuries. Kiel Bay in the western Baltic Sea is an example of such habitat. The future ocean acidification will be amplified in these areas, which could put their communities beyond their tolerance limits. At the moment, these areas can be used as model systems when testing responses of adapted marine ecosystems to high levels of acidification.



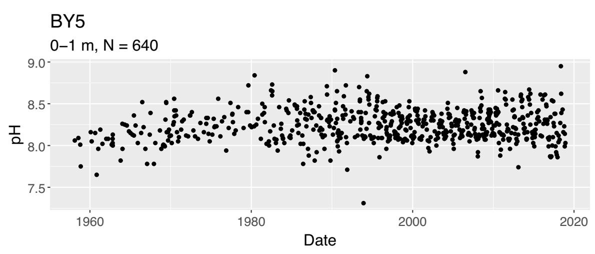


Figure 7. *Time series of pH in the surface water (0–1 m or 5 m) of the most frequently sampled monitoring station across the Baltic Sea. The graphs show changes in the sampling schedule, seasonal fluctuations, as well as a couple of possible decreasing long-term trends (US5B, LL7). Note that the accuracy of the data has changed over the years. (Data on NBS scale. Data: HELCOM, ICES Dataset on Ocean Hydrography, the International Council for the Exploration of the Sea, Copenhagen. 2014)*

Concluding remarks

In this report we have highlighted the ecological threats posed by ocean acidification, and the needs for mitigation and adaptation. We hope that this report will lead to further pressure for the improvement of policy and governance instruments that clearly are not up to date with regards to ocean acidification.

We encourage NGOs, universities and others to engage in public actions to raise awareness. To this end, the project has also published an action guide on ocean acidification, including the organising of an international ocean acidification week. The project strongly urges other NGOs and stakeholders to join forces to abate ocean acidification.

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Info box: Total alkalinity – the buffering capacity – of the Baltic Sea

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Effects on the Baltic Sea ecosystem

COASTAL ZONE

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