Ecological impacts of coastal protection measures on coastal ecosystems of the German Baltic Sea

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Abstract

Along the Baltic Sea coastline, several coastal protection structures are located to protect municipalities and infrastructure in the face of rising sea level and increasing frequency of storm surges. These structures can influence their surroundings, starting with alterations in the hydrodynamic conditions which can affect sediment characteristics and biodiversity. However, the spatial or temporal extent of these effects on the coastal ecosystems are mostly unknown. This applies for both conventional coastal protection structures and nature-based structures.

This dissertation focuses on the ecological consequences of four coastal protection measures (groynes, breakwaters, revetments and sand nourishments) on the directly affected but also on the neighbouring ecosystems at the German Baltic Sea coast. The primary objective was to investigate which of the following aspects of the ecosystems are altered by the coastal protection structures: sediment characteristics, nutrient concentrations in the pore water, turbidity and nutrients in the water column, and biodiversity in the shallow water as well as on beach and dune. The results show that all coastal protection measures have an impact on the coastal section they are designed to protect. However, the impacts differ dependent on the coastal protection structure used. Erosion-reducing conventional coastal protection structures lead to a stabilization of coastal ecosystems, which are reflected in the vegetation composition, developing towards rural or late dune succession stages, and altered sediment characteristics. In contrast to this, the research presented in this work shows that nature-based coastal protection structures focussing on compensation of alongshore sediment transport cause turbidity plumes, provide high amounts of nutrients for the water column and the terrestrial ecosystems and set back the dune succession to conditions similar to early dune succession stages.

In summary, this dissertation shows that all coastal protection measures exhibit ecological effects on the coastal ecosystems, which can vary greatly in terms of their direction of impact. These findings underscore the human impact on coastal ecosystems, even if some of the coastal protection measures are considered ecosystem-friendly, and should be taken into account when deploying or constructing new structures.

Zusammenfassung

Entlang der Ostseeküste befinden sich diverse Küstenschutzbauwerke, die Gemeinden und Infrastruktur vor dem steigenden Meeresspiegel und der zunehmenden Frequenz von Sturmfluten schützen. Diese Bauwerke können ihre Umgebung verändern, unter anderem die hydrodynamischen Verhältnissen, die sich auf die Sedimenteigenschaften und die biologische Vielfalt auswirken können. Das räumliche und zeitliche Ausmaß dieser Auswirkungen auf die Küstenökosysteme ist jedoch weitestgehend unbekannt. Dies gilt sowohl für konventionelle Küstenschutzbauwerke als auch für naturbasierte Maßnahmen.

Diese Dissertation befasst sich mit den ökologischen Auswirkungen vier Küstenschutzmaßnahmen (Buhnen, Wellenbrecher, Deckwerke und Sandaufspülungen) auf die direkt beeinflussten, aber auch auf die angrenzenden Ökosysteme an der deutschen Ostseeküste. Vorrangiges Ziel ist die Klärung, welche der folgenden Aspekte der Ökosysteme durch die Küstenschutzmaßnahmen verändert werden: Sedimenteigenschaften, Nährstoffkonzentrationen im Porenwasser, Trübung und Nährstoffe in der Wassersäule, sowie die Artenvielfalt im Flachwasser und auf Strand und Düne.

Die Ergebnisse zeigen, dass alle Küstenschutzanlagen einen Einfluss auf die von ihnen geschützte Küstenabschnitte haben, dieser Einfluss unterscheidet sich jedoch nach verwendeter Struktur. Konventionelle erosionsmindernde Küstenschutzbauwerke führen zu einer Stabilisierung der Küstenökosysteme, was sich in der für rurale oder späte Dünensukzessionsstadien typischen Vegetationszusammensetzung und in veränderten Sedimenteigenschaften widerspiegelt. Im Gegensatz dazu führen naturbasierte Küstenschutzmaßnahmen, die sich auf die Kompensation des küstenparallelen Sedimenttransports konzentrieren, zu Trübungswolken, liefern große Mengen an Nährstoffen für die Wassersäule und die terrestrischen Ökosysteme und verursachen Bedingungen ähnlich zu frühen Dünensukzessionsstadien.

Zusammenfassend zeigt diese Dissertation, dass alle Küstenschutzmaßnahmen ökologische Auswirkungen auf Küstenökosysteme haben, diese jedoch in ihrer Wirkungsrichtung sehr unterschiedlich sein können. Diese Ergebnisse unterstreichen den Einfluss des Menschen auf die Küstenökosysteme, auch wenn einige der Küstenschutzanlagen als ökosystemfreundlich gelten, und sollten bei der Einführung oder dem Bau neuer Anlagen berücksichtigt werden.

List of abbreviations

BP	before present
et al.	et alia (and others)
e.g.	exempli gratia (for example)
Fig.	Figure
pH	negative decimal logarithm of the hydrogen ion activity in a solution
s. l.	sensu lato (in the broader sense)
sp.	species
°C	degrees Celsius

List of figures for Part I

Part I: Synthesis of the doctoral study

1 Typology of coastal protection strategies

The Baltic Sea coast in Mecklenburg-Western Pomerania represents a dynamic transition zone between terrestrial and marine ecosystems that is characterised by unique environmental conditions (Radziejewska et al. 2017). The reciprocal influence of land and sea leads to special features in the coastal habitats impacting the adapted organisms that live there. These features include, above all, factors that limit growth or even survival, including water supply, mechanical stress due to sediment transport and the supply of nutrients (Hesp 1991, Kiehl and Kollmann 2019). Especially the presence of abundant brackish water on one side and limited freshwater on the other side creates a challenging environment for organisms that have to cope with both (Kiehl and Kollmann 2019). At the same time, the Baltic Sea is an eutrophic system (HELCOM 2023), whereas beaches and dunes are nutrient-limited ecosystems (Kiehl and Kollmann 2019). Fluctuating water levels caused by wind and waves require organisms to either withstand these changes or relocate accordingly (Kiehl and Kollmann 2019). Additionally, hydrodynamic forces drive the sediment transport between land and water (Radziejewska et al. 2017) and characterize the two main coastal structures types at the German Baltic Sea coast, which are cliffs and sandy coasts (Fig. 1). Sediment is removed from the eroding parts of cliffs and transported parallel to the coast to be deposited on the calm coastal sections where it can form sandy beaches and dunes (Jurasinski and Buczko 2023).

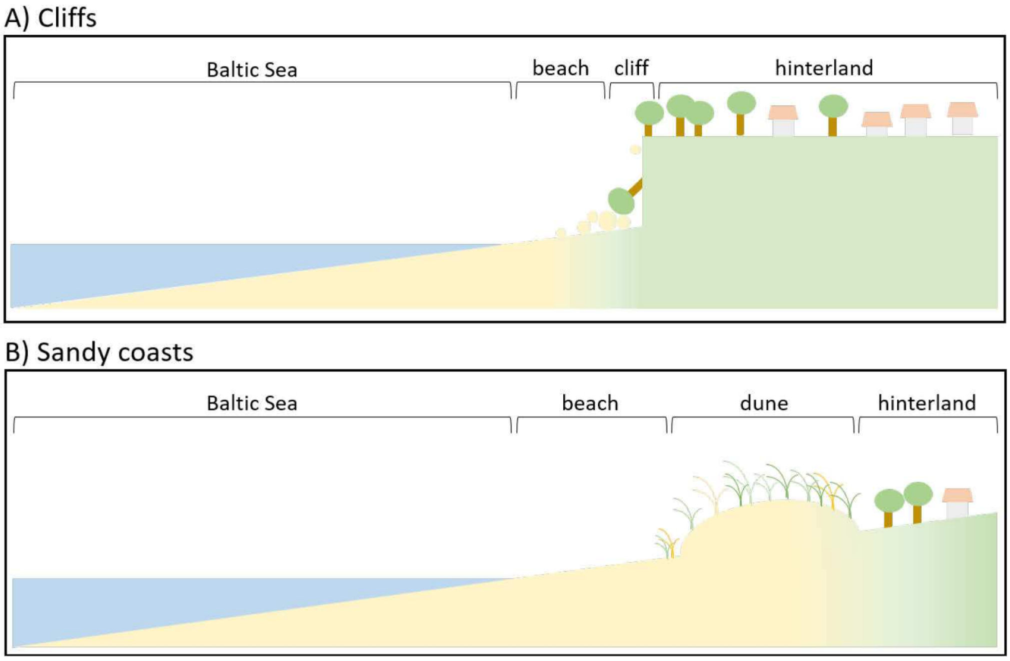

Figure 1: Main coastal structure types at the German Baltic Sea coast in Mecklenburg-Western Pomerania. Eroding cliffs provide the sediment for sandy beaches and dunes.

These processes of sedimentation and erosion on cliffs as well as sandy beaches, affect the distribution of organisms (Tõnisson et al. 2014, van Puijenbroek et al. 2021). Anthropogenic coastal barriers, e.g. coastal protection structures, can alter the natural dynamics of sedimentation and erosion, resulting in short or long term changes in surrounding ecosystems (Schoonees et al. 2019). These changes in turn can be used as indicators for the degree of impact caused by different kinds of coastal protection structures, allowing for the development of low-impact measures preserving crucial functions of the coastal ecosystems.

Currently, over 339 km of the German Baltic Sea coast in Mecklenburg-Western Pomerania are protected by some kind of technical coastal protection structures which corresponds to almost 20 % of the total coastline (MLUV MV 2009). This widespread attention to and systematic implementation of coastal protection structures was initiated and is the result of the first half of the 19th century due to the increasing frequency of severe storm surges (Charlier et al. 2005, Dugan et al. 2011). At this time, systematic coastal and flood protection efforts were mostly consisting of dunes stabilized by wooden piles. But with increasing human use of the coast, and therefore increasing human pressure on the coastal ecosystems, a more comprehensive approach evolved, consisting of dikes, groynes, sand nourishments, revetments and other structures (Dugan et al. 2011, Kabat et al. 2009, MLUV MV 2009).

Dunes are still the most essential part of the coastal protection at the Baltic Sea coast in Mecklenburg-Western Pomerania in terms of protected coast length (MLUV MV 2009). Coastal protection dunes are inspected continuously (Firth et al. 2016), because their effectiveness relies on the status of their wear parts. The wear parts are reduced by aeolian erosion, floods and storm induced erosions and are expected or designed to break over time. Therefore, these wear parts must be replaced by sand nourishments to maintain their protective shape (Kortekaas et al. 2010, MLUV MV 2009). To prolong the duration of the sand nourishments, the combined installation of groynes is favoured (MLUV MV 2009, Simm et al. 2020). Groynes are the second most important coastal protection measure and are installed along 79 km of the outer coast of Mecklenburg-Western Pomerania, reducing alongshore transport of sediment. Mainly, single-row wooden pile groynes are used, but other modifications such as double-rows or double-rows with additional concrete fillings exist (MLUV MV 2009). Dikes are the third largest coastal protection measure, protecting 45 km of the coast. In contrast to dunes, dikes shall not have wear parts. Being expensive to build compared to other measures, they are almost exclusively protecting areas of special interest as towns and critical infrastructure. Other coastal protection measures protect each less than 20 km coastline (Fig. 2). These measures consist of a total of 16 km revetments, 10 km seawalls, 5 km stone walls, 4 km breakwaters, 4 km rubble walls and 1 km geotextile structures along the coastline (MLUV MV 2009). Without those coastal protection measures, a storm flood could cause the widespread flooding of an area estimated around 1080 km², affecting 11 % of the population in the federal state Mecklenburg-Western Pomerania. Despite the coastal protection measures, however, around half of Germany's Baltic Sea coast is still at risk of flooding today (MLUV MV 2009).

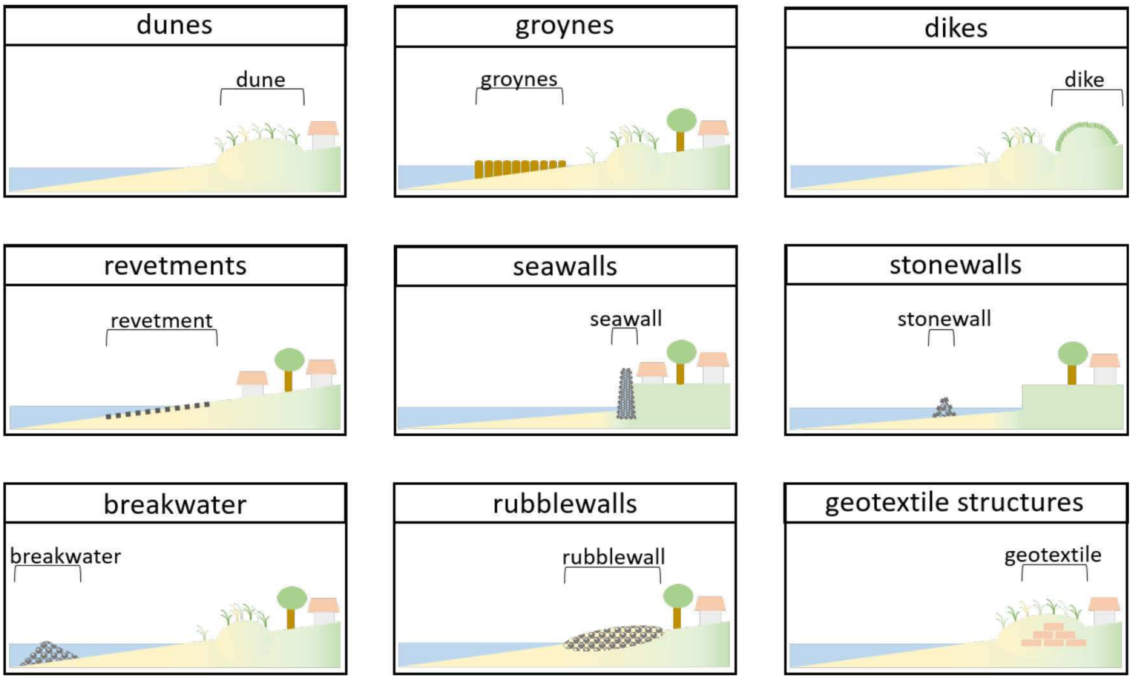

Figure 2: Designs of coastal protection measures used at the Baltic Sea coast in Mecklenburg-Western Pomerania, Germany.

Coastal protection measures are classified into different categories, namely conventional measures, also referred as hard or grey structures, and nature-based measures, which are often called green structures (Schoonees et al. 2019). Examples for conventional structures are seawalls, dikes, groynes or breakwaters (Hamm et al. 2002, Schoonees et al. 2019). These structures have been deployed in coastal areas for decades, resulting in a vast variety of guidelines for best practice (Schoonees et al. 2019). However, with increasing awareness for and interest in a sustainable development of the coast, the demand for alternative measures rises (Capobianco and Stive 2000, Hamm et al. 2002, Jordan and Fröhle 2022). The main aim is to reduce the potential negative effects of conventional structures, such as separating ecosystems (Bishop et al. 2017) and modifying sedimentation patterns (Dugan et al. 2011), by replacing them with stabilization measures considered almost natural or natural. These alternative, nature-based measures can be divided into three subcategories according to Schoonees at al. (2019): hybrid structures which include a combination of conventional and nature-based structures (e.g. seawalls with salt marshes in front), environmentally friendly conventional structures (e.g. vegetated revetments) and soft structures, referring mostly to ecosystem engineering (e.g. salt marshes and dunes). At the German Baltic Sea coast, structures from different categories and subcategories are present (Fig. 3).

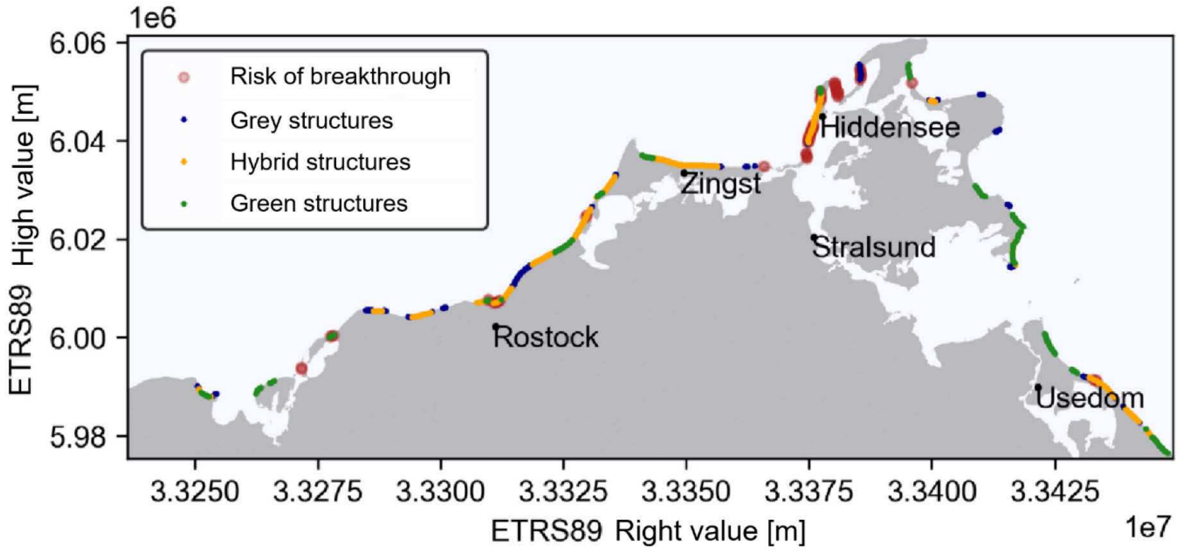

Figure 3: Coastal sections in Mecklenburg-Western Pomerania, Germany, that are protected by coastal protection measures. These are divided into grey, hybrid and green structures. Translated but unmodified version of Tiede et al. (2022).

Another classification of coastal protection measures is based on the location of the structure itself. While some structures are placed in the foreshore, either parallel or perpendicular to the shore, others are built onshore. These structures differ in their primary task: foreshore structures are meant to counteract erosion (Hamm et al. 2002), e.g. breakwaters have a sheltering effect on the coast, groynes slow down the alongshore sediment transport and foreshore nourishments compensate eroding environments (Schoonees et al. 2019, van Rijn 2013). Onshore structures provide protection of the hinterland from flooding by fixing the shoreline, e.g. through seawalls, nourished dunes or dikes (Schoonees et al. 2019).

2 Environmental impacts of coastal protection measures

Although location, material and main function varies in conventional coastal protection structures, they constitute an intervention causing environmental impacts in otherwise dynamic habitats. This starts with the risk of disrupting land-sea connectivity by putting barriers between ecosystems; either between two terrestrial ecosystems or between the terrestrial and the marine ecosystems (Bishop et al. 2017). The degree of separation not only depends on the characteristics of the structure itself, but also on those of the residing organisms (Bishop et al. 2017). For example, Dugan et al. (2011) reported effects on the nesting of birds and sea turtles as their nesting habitat is eliminated by introducing conventional coastal protection structures to the upper beach. Accordingly, the introduction of hard substrate can also change the local biodiversity in coastal regions by modifying dispersal patterns (Bulleri and Chapman 2010). Interventions in trophic connections occur as a result of changes in community structures (Bishop et al. 2017).

Especially conventional coastal protection measures can exterminate ecosystems completely. An example for this are revetments covering the area between mean water level and anthropogenic infrastructure. In this scenario, both beach and dune ecosystem are replaced by an artificial structure and no longer exist in their original form (Schoonees et al. 2019). But also if kept to a certain degree, sandy beaches and dunes recently face a considerable threat known as coastal squeeze (Doody 2004, Firth et al. 2016). For the terrestrial part, Grunewald (2006) has shown that plant diversity and vegetation cover diverted from the natural status with increasing human impact. In the marine part, especially macrophytes have proven to be vulnerable to anthropogenic pressure (e.g. Jordan and Fröhle 2022). To summarize, coastal interventions leading to biota burial and habitat loss (Schoonees et al. 2019) contribute to the reduction of essential ecosystem functions (Dugan et al. 2011, Jordan and Fröhle 2022).

Apart from covering existing vegetation or deterioration of environmental conditions, further alterations occur in form of modified sediment dynamics and depositional processes (Nordstrom et al. 2004, Schoonees et al. 2019). The main functions of conventional coastal protection measures are the interception and dissipation of wave energy or currents, reducing their erosive power. This protection against erosion also includes protection against sliding, e.g. of cliffs or dunes (van Rijn 2013). In order to fulfil the task in maintaining the shoreline, conventional coastal protection measures exert an influence on the morphological and hydrodynamic situation near the coast (Dugan et al. 2011). This leads to modifications in the water transport around these structures by acceleration and deceleration of the transport, thereby causing scour erosion or deposition (Hall and Pilkey 1991, MLUV MV 2009, Schoonees et al. 2019). These processes can reach an equilibrium leading to stabilization of the deposition zone and only minimal erosion, but the time scale is dependent on the size of the conventional coastal protection structure and the site and its longshore sediment transportation rates. Especially during the installation of these structures, maximum accretion and erosion can already lead to significant morphological changes along the coastal stretch (van Rijn 2013).

The deployment of hard coastal protection structures can further result in unexpected and unwanted consequences. Firth et al. (2016) and van Rijn (2013) are listing increased wave reflection, changes in current velocities, turbulence intensities and alongshore transport capacities, and destruction of the natural bar-and-trough pattern, all leading to profile steepening and increased offshore transport in the marine part of the coastal zone, causing delayed or reduced beach and dune recovery and intensified shore face- and lee-side erosion at the terrestrial part. As a consequence, the shoreline may even retreat, contrasting the primary task of coastal protection measures in fixing the coastline (Firth et al. 2016, van Rijn 2013).

Studies by Dugan et al. (2011) as well as Airoldi and Beck (2007) highlight that the impact of hard substrates increases if placed in areas adjacent to soft substrates. This not only applies to hydrodynamics, but also biota. Martin et al. (2005) reported changes in composition of macrobenthic assemblages which become more pronounced with increasing proximity to the hard structures introduced. This applies for a number of different conventional coastal protection structures, such as low crested structures and groynes (Bacchiocchi and Airoldi 2003, Martin et al. 2005), but not nature-based coastal protection measures (van Egmond et al. 2018).

Besides a decrease in abundance of organisms, another response to the introduction of artificial substrates can be the appearance of certain species in extremely high numbers, e.g. the amphipod *Corophium* sp. near breakwater and groynes (Martin et al. 2005). However, these changes appear to be reversible. After dismantling parts of the coastal protection structures and turning coastal stretches into so called living shorelines, an increase in biomass of larger infauna (> 3 mm) was reported, mostly consisting of clams, while a decrease in polychaetes was detected. Davenport et al. (2018) suggested this as a transition towards more stable communities at the shoreline and a return to an almost normal state. Overall, changes in species abundancy and diversity may results in alterations of functional groups (Momota and Hosokawa 2021). Therefore, coastal areas with coastal protection measures are often regarded as strongly transformed ecosystems (Airoldi et al. 2005, Gittman et al. 2015). On the other hand, Martin et al. (2005) found only small changes in trophic structures, mostly just the replacement of certain species by competitors of the same trophic level. Taking into account that the latter investigation originates from a species-depleted region of the Baltic Sea, the question whether all trophic levels can be maintained in general remains open.

Undisputed, however, is the role of hard substrates in offering new habitats for both macroalgae and zoobenthos, potentially expanding the distribution of both native and non-native species (Airoldi and Beck 2007, Firth et al. 2016). Especially hard coastal protection structures can serve as pivotal stepping stone biotopes with significant implications: novel ecological niches can favour the invasion of alien species, marking coastal protection areas as potentially dynamic landscapes for ecological succession (Airoldi et al. 2005, Olenin et al. 2017). This is reflected by the observation that non-indigenous species are more frequent on artificial structures compared with nearby natural habitats (Airoldi et al. 2015, Firth et al. 2016, Olenin et al. 2017, Schoonees et al. 2019). One example for this are wooden groynes, serving as habitats for *Teredo navalis* L. in the Baltic Sea from the Danish Straits to Rügen (Lippert et al. 2017, MLUV MV 2009). However, indigenous species can also spread in this way. To increase beneficial effects on those indigenous species, ecological engineering by creating microhabitats (Firth et al. 2016) has been introduced to coastal measures but far-reaching studies are still pending. But even with hard structures designed to imitate natural reefs, there are still concerns as to whether they can really achieve this goal (Dugan et al. 2011, Firth et al. 2016).

Not only grey, but also nature-based coastal protection structures cover large areas of the coast and add to the coastal squeeze, limiting the opportunity for individuals to migrate up-shore to escape rising sea levels (Doody 2004, Firth et al. 2016). Examples are vegetated revetments or artificially designed dunes, maintained by sand nourishments. In contrast to conventional structures, nature-based structures try to imitate natural conditions (Silva et al.

2017). Still, the construction of these nature-based structures destroy and bury the preceding ecosystems, contributing to habitat loss and modifying essential ecosystem functions (Dugan et al. 2011, Jordan and Fröhle 2022). However, it is noteworthy that some of these nature-based coastal protection measures increase nutrient availability, resulting in increased vegetation cover (Grunewald 2006). This enables faster recovery of biodiversity after interventions. But this newly developed vegetation differs from the naturally occurring vegetation as most of the species are adapted to eutrophication, leading to alterations in biotic structure (Schoonees et al. 2019). Moreover, since it became common practice to support fast development of dune vegetation cover by planting, the choice of species for the respective measure became important too. Dikes and dunes differ with respect to the abiotic settings and, in addition, the plants used for planting should also be ecologically valuable in view of the measure to be declared as near-natural (Schoonees et al. 2019). Consequently, the long-term success of a coastal protection measure depends on the selection of species appropriate to the respective sediment conditions (Gracia et al. 2021).

Some nature-based coastal protection measures, most prominent sand nourishment, include a transfer of sediment from offshore accumulation areas to the coast in order to compensate for erosion losses. With recent technologies, discharge of suspended sediment at both sides are unavoidable and can cause the loss of seagrass and macroalgae due to increased turbidity, as documented by Airoldi and Beck (2007), Jordan and Fröhle (2022) and Schoonees et al. (2019). The rise in turbidity is reducing the depth limit for macrophytobenthos (Zettler et al. 2017), negatively impacting ecosystem health. However, there are also natural events releasing substantial sediment loads in the water column and increasing turbidity as, e.g. storm events and cliff breaks (Jarmalavičius et al. 2016, Sterr 1989). Storm events can cause large-scale erosion on the coast through waves promoting changes directly by overwashing, flooding and wave induced currents that transport sediments (Labuz and Kowalewska-Kalkowska 2011). Even cliff breaks, irrespective of being spatially limited (Mattheus and Diggins 2019), discharge large amounts of sediment causing temporary turbidity clouds travelling with currents along the shoreline (Mossbauer 2008, Fig. 4). To what extent such natural events are comparable to the effects of coastal protection measures still needs to be investigated, especially concerning the unique conditions of the Baltic Sea.

Figure 4: Natural turbidity cloud at the German Baltic Sea coast. Part of the island of Hiddensee in Mecklenburg-Western Pomerania, Germany, can be seen. Photo taken by Hendrik Schubert on 15th April 2001.

3 Coastal and marine ecosystems of the Baltic Sea

Apart from eustatic sea-level rise, isostatic rebound causes long-term shifts of sea level along the Baltic Sea coasts (Snoeijs-Leijonmalm 2017). Isostatic rebound in the Baltic Sea area is the consequence of loss of the Weichselian ice sheet at > 10000 years BP. This process results in contrasting effects, manifesting in land uplift in Sweden and land subsidence in Germany (Köster 1996, Winterhalter et al. 1981). As a result, two contrasting coastal bottom types shape the coastline of these countries. While in Sweden solid stone bottoms dominate, a pattern of eroding chalk and marl cliffs with sandy and soft bottom stretches between them are characteristic for the southern German Baltic Sea coastline (Winterhalter et al. 1981). This geological background leads to a pronounced sediment dynamic along the coast of Mecklenburg-Western Pomerania. The erosion of cliffs is feeding sandy beaches by alongshore sediment transport; sedimentation processes in calm zones may even seal off former sea bays (Fig. 5). In Mecklenburg-Western Pomerania, three main types of coastal morphology are distinguished: the Large Bay Coast (Großbuchtenküste), defined by a landscape of young glacial origin and marked by a strong moraine relief (MLUV MV 2009, Winterhalter et al. 1981), the Equilibrium Coast (Ausgleichsküste) characterized by a highly indented coastline, which became gradually smoothed by the formation of shallow and sandy coasts, and the Bodden Equilibrium Coast (Boddenausgleichsküste) with partly strongly reduced coastal dynamics and sedimentation processes (Lampe 1996). Overall sediment transport capacities on the German Baltic Sea Coast are estimated to reach up to 200,000 m³ per year, underlining the dynamic nature of coastal evolution (MLUV MV 2009).

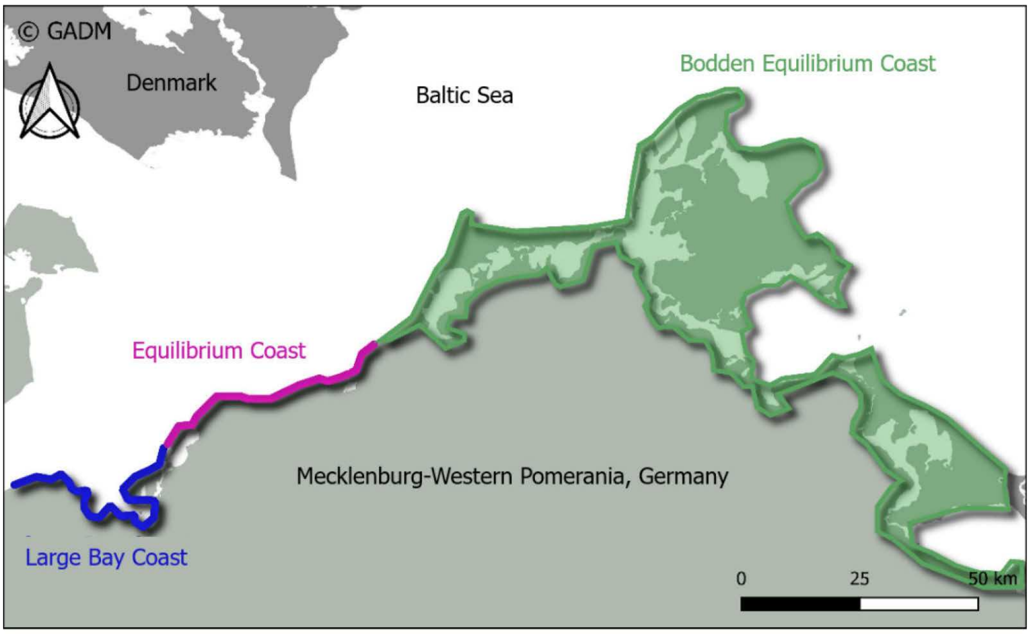

Figure 5: Morphological coastal types at the coast of Mecklenburg-Western Pomerania, Germany. Map data: © 2024 GADM (Database of Global Administrative Areas).

Unlike many other coastal regions, the Baltic Proper experiences only minimal sea level changes caused by differences in atmospheric pressure and wind conditions (Hällfors et al. 1981). This results in a littoral zonation in geolitoral, ranging from the lower limit of terrestrial plant growth to the mean (summer) sea level, and hydrolitoral, ranging from mean (summer) sea level to the lowest sea level (Du Rietz 1950). Moreover, this shallow brackish sea has only limited water exchange with the global ocean occurring through the Danish Straits (Ehlin 1981, Snoeijs-Leijonmalm and Andrén 2017, Winterhalter et al. 1981). A more substantial influx of freshwater comes from over 200 rivers (Ehlin 1981, Snoeijs-Leijonmalm and Andrén 2017). This exceptional combination of conditions create a complex salt gradient in the Baltic Sea, marked by substantial regional differences in surface salinity (Hällfors et al. 1981). A large part of the Baltic Sea is considered mesohaline, with salinity levels ranging between 5 and 10 (Hällfors et al. 1981, Schubert et al. 2017).

When considering vegetation biodiversity of the Baltic Sea, all elements belonging to the marine realm (i.e. beaches, dunes and the submerged flora) must be taken into account. While the Baltic Sea Area (including the transition zone) harbours an impressive 531 species of macrophytobenthos, the species richness within the Baltic Sea alone is only one-third of that (Snoeijs-Leijonmalm 2017). In the south to southeast stretches, the Baltic Sea bottom predominantly consists of mobile sediments (Winterhalter et al. 1981), providing a habitat for the seagrass species *Zostera marina* L.. Most seagrass meadows were found in between 0.6 and 7.6 m depth (Schubert et al. 2015). This depth zone is - directly (construction of stonewalls, groynes and breakwaters) or indirectly (sediment cover and increased turbidity during installation) - impacted by coastal protection measures, creating potential conflicts with nature conservation principles. The sandy sections of the coast are repeatedly interrupted by natural reefs or other hard substrates, offering attachment options for macroalgae and contributing to the overall biodiversity of the Baltic Sea (Hällfors et al. 1981, Snoeijs-Leijonmalm 2017, Fig. 6).

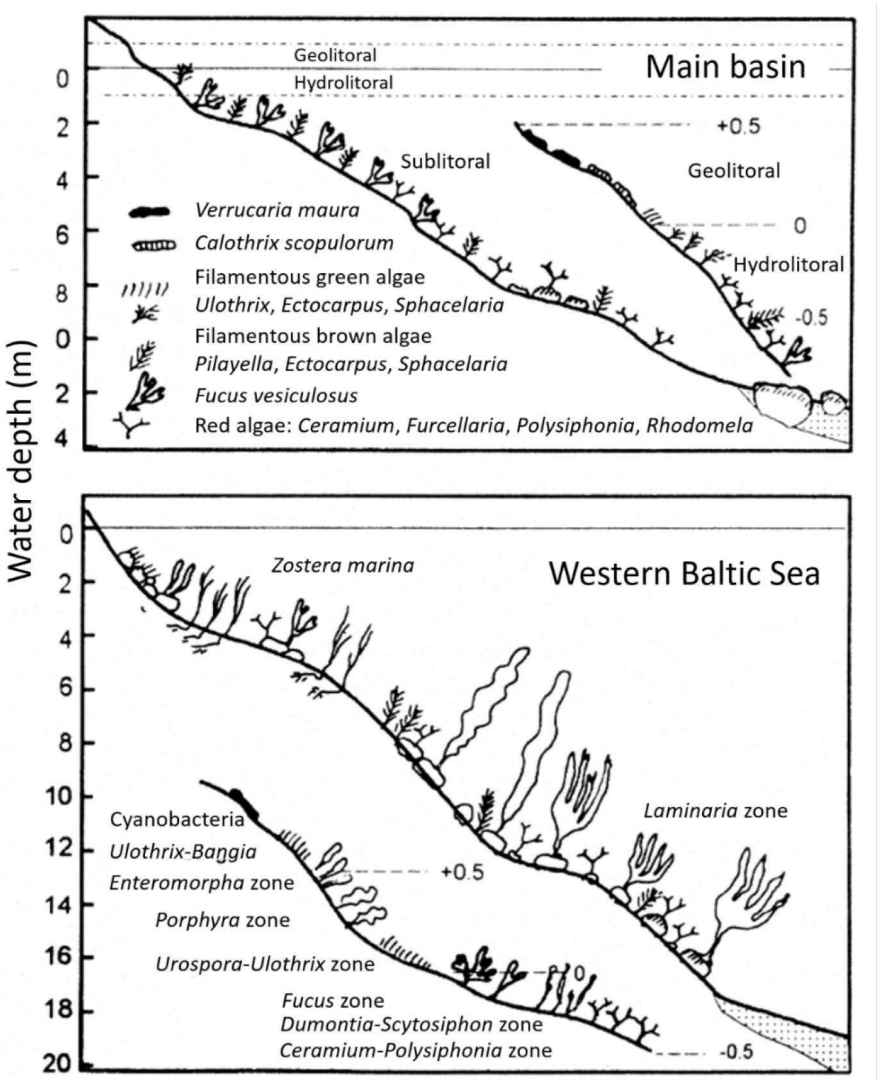

Figure 6: Zonation of macrophytobenthos in the central and western Baltic Sea. Figure modified and translated after Schwenke (1996).

However, hard substrates are limited in the Baltic Sea, primarily consisting of boulders, mussel shells and artificial substrates (Hällfors et al. 1981). These hard substrate areas exhibit monotonous belts featuring only few species of macroalgae, including *Fucus vesiculosus* Linnaeus and *Furcellaria lumbricalis* (Hudson) J.V.Lamouroux. Species such as *Cladophora glomerata* (L.) Kützing thrive in the upper meter of the hard substrate environments (Snoeijs-Leijonmalm 2017) and in polluted and nutrient enriched waters (Markert et al. 2003). Along the Baltic Sea salinity gradient, the number of macroscopic algae and plant species declines with decreasing salinity and several marine algae exhibit a gradual reduction in size and reproductive cycle (Hällfors et al. 1981, Snoeijs-Leijonmalm and Andrén 2017).

As with the marine part of the coastal ecosystem, a clear zonation can also be observed along the terrestrial beach-dune systems. Dune formation is a dynamic process influenced by various factors and happens at the wind-exposed side along the coast while the wind-protected side fosters the development of salt marshes (Boedeker and Knapp 1996, Kiehl and Kollmann 2019). The interplay of wind, sand dynamics and salt stress decreases with increasing distance to the sea and manifests in an ecological differentiation (Fig. 7). This displays as a zonation with varying vegetation types (Ellenberg and Leuschner 2010, Maun 2009). The residence time of the sand plays a crucial role in this zonation, as with increasing age leaching lowers pH and, simultaneously, development of vegetation increases carbon and nitrogen content in the soil (Ellenberg and Leuschner 2010).

The first step of dune development always is a sand accumulation persisting for a sufficient period to establish a pioneer vegetation In order to grow beyond the limits set by the nutrients supplied by the seeds, additional sources of nutrients as, e.g. beach wrack accumulations, are required (McLachlan and Brown 2006). Such dunal pioneers are drought-resistant grasses, e.g. *Leymus arenarius* (L.) Hochst. and *Elytrigia junceiformis* (Á. Löve & D. Löve) Hand & Buttler, as well as succulent species like *Cakile maritima* Scop. and *Salsola kali* L. s. l. , and steppe plants (including *Atriplex littoralis* L.), all converting the barren sand accumulation to a vegetated primary dune. Despite the stabilization provided by rhizomes, primary dunes face numerous challenges such as salt stress, flooding, prolonged dryness, sand cover and nutrient deficiency. Therefore, the initial dune stages' vegetation reaches only relatively modest heights, typically up to one or two meters (Kiehl and Kollmann 2019, Maun 2009, McLachlan and Brown 2006).

The dynamic process of dune formation persists as wind drift transports sand towards the land, giving rise to foredunes, also known as secondary dunes. Secondary white dunes can reach impressive heights, ranging from 10 to 30 meters. The stabilizing influence of the large rhizomes of *Ammophila arenaria* (L.) Link plays a pivotal role in this growth. The plants do not only catch sand but can also grow through up to 40 cm of sand if buried underneath (Kiehl and Kollmann 2019, McLachlan and Brown 2006). The habitat of these evolving dunes is still subject to the constant interplay of wind-driven sedimentation and erosion (Kiehl and Kollmann 2019, Maun 2009). The sand contributing to the dune composition is lime-rich with a high pH but lacks humus (Ellenberg and Leuschner 2010). Within this challenging environment, *Ammophila arenaria* (L.) Link demonstrates a competitive edge over other plants. However, a coexistence is achieved as various herbs manage to thrive in this dynamic habitat. Species such as *Eryngium maritimum* L., *Lathyrus japonicus* Willd., *Carex arenaria* L. and *Festuca rubra* L. coexist, contributing to the ecological richness of the evolving dune landscape.

On the wind-sheltered side of the foredune, a transition unfolds, marking the shift to a grey dune characterized by changing microclimate and soil conditions (Kiehl and Kollmann 2019). In this zone, the environment remains dry, but the wind is decreasing. The leaching of soil, while facilitating humus accretion, creates acidic conditions and increases nutrient availability (Ellenberg and Leuschner 2010). Sandy grasslands, featuring dominant species such as *Corynephorus canescens* (L.) P.Beauv., *Carex arenaria* L., *Jasione montana* L. (Kiehl and Kollmann 2019), as well as pioneer mosses and lichens (McLachlan and Brown 2006), contribute to the biodiversity of the grey dune. As the dune ages, stabilization intensifies and brown dunes are forming. They are covered by either oak-birch forests or heaths, and in the Baltic Sea region, occasional pioneer pine forests. The rich tapestry of vegetation includes species like *Calluna vulgaris* (L.) Hull, *Hieracium umbellatum* L., and *Salix repens* L. s. l. (Kiehl and Kollmann 2019). A thick cover of humus blankets the top layer of the otherwise acidic and nutrient-poor soil (Ellenberg and Leuschner 2010).

The result of the dune formation is a landscape that is characterized by rows of dunes, interspersed with moist dune valleys (Fig. 7). The valleys can harbour shallow water bodies or damp sites, offering conditions even enabling peat formation (Kiehl and Kollmann 2019, Maun 2009, McLachlan and Brown 2006). Despite the generally stable zonation of dunes, the potential for development persists during their lifetime. Within a few years, a primary dune can transition to a white dune, followed by a progression to a grey dune within 10 – 20 years and ultimately maturing into a brown dune over 60 – 70 years (Kiehl and Kollmann 2019). However, this natural progression is not immune to interventions, such as storm floods, land subsidence and other threads, that can hinder development or even cause regression (Kiehlt and Kollmann 2019, Maun 2009).

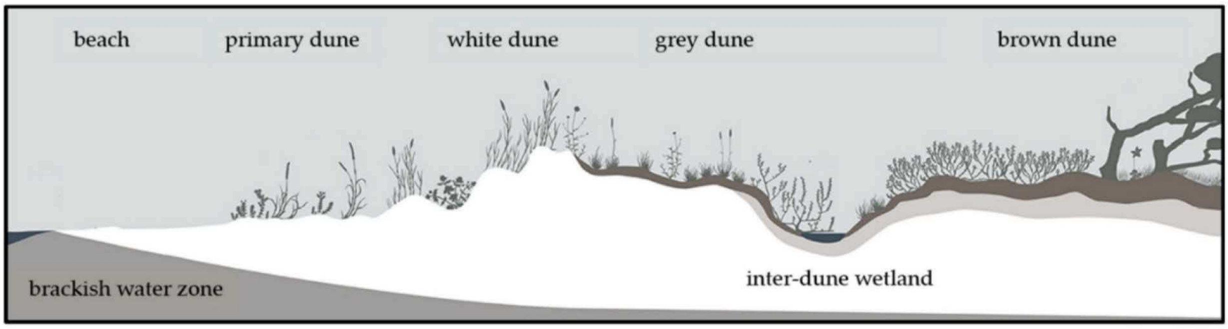

Figure 7: Cross-sectional overview of the stages of dune development and the most common terminology for the German Baltic Sea coast. Adapted with permission from Botanical Garten, University of Rostock (2024).

Coastal ecosystems do not only serve as vital habitats for plants and animals (Kiehl and Kollmann 2019), they also provide benefits for humans. These are called ecosystem services (World Resources Institute 2005). They include the historical context of land use, e.g. grazing pasture, firewood harvesting, mowing, extraction of turfs for thatched roofs, but also very recent roles in providing drinking water and serving as a frontline defence in coastal protection efforts (Kiehl and Kollmann 2019). The quantification of these ecosystem services remains a complex endeavour. The most successful approach in providing help for planning processes, are cautious comparisons of different coastal protection measures (Schernewski et al. 2022, Schernewski et al. 2023).

The overall ecological condition of the coast is dependent on many factors including both abiotic, e.g. sedimentation and water quality, as well as biotic conditions, e.g. dune and underwater vegetation (Radziejewska et al. 2017). The increase in coastal protection along the coast has led to changes in coastal ecosystems. Protected cliffs cannot supply the sediment needed to stabilize eroding beaches and dunes. Therefore, coastal protection along these beaches and dunes has increased, resulting in strongly fixed shorelines via conventional structures (e.g. revetments) or stabilized shorelines with at least some variability via nature-based measures (e.g. sand nourishments). These changes affect again the patterns of erosion and accretion of sediment, as well as hydrodynamic conditions including wave patterns and are a cause of placement loss (Schoonees et al. 2019). Additionally, it is known that coastal protection measures can disturb certain key species in dunes. An example for this are dune grasses that perform natural ecosystem engineering functions (Groot et al. 2017). Without these key species, increased shrub invasion, eutrophication and a decline in species diversity are possible developments (Kiehl and Kollmann 2019). Therefore, the assessment of coastal protection measures in terms of biodiversity consequently requires a differentiated understanding of the ecological impacts. Evaluating coastal protection strategies through an ecological lens is crucial for understanding the implications on biodiversity conservation and for promoting sustainable management practices. Against this background, the work presented here focuses on the ecological implications of coastal protection measures along the German Baltic Sea coast.

4 Background and objectives

To address this focus, this dissertation centres on the differences between sites at the German Baltic Sea coast with coastal protection measures and control sites without coastal protection measures in the same region. This dissertation wants to contribute to the fundamental understanding of the ecological effects of various coastal protection measures. This thesis evaluates habitat changes caused by both conventional hard structures (groynes, breakwaters and revetments in **publication II** and **III**) and nature-based measures (sand nourishments in **publication I**, **II** and **IV**), which are among the most commonly used measures on the German Baltic Sea coast.

Today both conventional and nature-based coastal protection structures exist on the German Baltic Sea coast. However, nature-based coastal structures are only being constructed for a few decades and coastal protection was characterised by exclusively conventional structures for a long time (MLUV MV 2009). First traces of constructed dikes at the North Sea coast can be dated back to the 11th century (Behre 2023), while systematic dike construction at the German Baltic Sea coast only began in the 19th century (MLUV MV 2009). There, the first systematic coastal protection began in the first half of the 19th century and was further reinforced in its second half and in the 20th century after various storm surges, subsequently covering several dozen kilometers of coastline (MLUV MV 2009). This systematic protection was continually expanded until it formed today's traditional system. It consists of groynes, coastal protection dunes, coastal protection forests and dikes. This conventional coastal engineering has been seen as the ultimate solution for coastal protection in most cases (Temmerman et al. 2013). However, negative effects of these conventional structures on morphological and hydrodynamic conditions of coastal habitats were reported: they particularly affect the sediment transport along the coast hindering the natural accumulation of sediments (Schoonees et al. 2019, Temmerman et al. 2013). These consequences are in contradiction to the actual objective of the coastal protection measures and can even lead to accelerated erosion of coastlines (Martin et al. 2005, Schoonees et al. 2019).

Due to the hydrodynamic and morphological consequences of conventional protection measures, criticism and the wish for alternatives arose in the second half of the 20th century. At the same time, the desire for more aesthetic solutions, growing tourism, increasing environmental awareness and the expansion of protected areas - such as national parks (Bundesamt für Naturschutz 2023) - have fuelled a demand for more environmentally-friendly coastal protection measures. These nature-based approaches aim to balance coastal protection with ecological considerations to mitigate environmental impacts (Schoonees et al. 2019). Nature-based coastal protection measures also include coastal habitats that naturally fulfil a coastal protection function. According to Firth et al. (2016), natural coastal protection mechanisms include biogenic habitats (e.g. kelp forests, seagrass meadows, mangroves, salt marshes, corals and mussel reefs) but also geogenic habitats (e.g. rocky coasts and sandy habitats). At the Baltic Sea Coast in Mecklenburg-Western Pomerania, especially sandy habitats such as dunes and beaches are used for environmentally friendly coastal protection particularly in the context of sand nourishments (MLUV MV 2009).

Coastal protection structures along parts of the German Baltic Sea coast are needed to enable the coastal municipalities to thrive. Nevertheless, the planning for these protection measures should not be performed solely on the basis of protection of human infrastructure but also include the conservation of important ecosystems. In order to better assess the impact of human intervention in the coastal areas of the German Baltic Sea, the investigation of the following hypotheses were used to shed light on the ecological effects of coastal protection measures on coastal ecosystems.

Hypothesis 1: Coastal protection leads to short-, mid- and long-term changes in sediment and nutrient conditions in the coastal zone.

In **publications I**, **II**, **III** and **IV**, the sediment and nutrient conditions of coastal sediments and water samples at four different coastal protection sites at the German Baltic Sea coast were analysed by using sediment cores and water samples taken at dunes, beaches and in the shallow water. The coastal protection structures are groynes, sand nourishment, revetment and breakwater. **Publication I** focuses on the turbidity in the water column caused by sand nourishments in comparison to naturally occurring disturbances, e.g. storm events.

Hypothesis 2: Changes in sediment und nutrient conditions in the coastal zone caused by coastal protection measures impact the biodiversity and the dune succession of the coasts in Mecklenburg-Western Pomerania, Germany.

In **publication II** and **III**, the biodiversity of higher plants, mosses and lichens in coastal areas was evaluated based on data recorded during transect monitoring. The same locations were used for this as for the other analyses. The biodiversity in the shallow water was included in **publication III**, as hard substrate was introduced at the highlighted site.

Hypothesis 3: The effects of the changes in sediment and nutrient conditions in the coastal zone due to coastal protection measures, as well as the effects on the biodiversity and the dune succession, vary depending on the coastal protection measure.

Publication II, **III** and **IV** show differences concerning impacts on biodiversity, sediment and nutrient conditions when comparing two coastal protection measures. Additionally, a complete comparison of all recorded alterations at the different sites will be performed in the synthesis of this doctoral thesis.

5 Study sites of the dissertation

On the Baltic Sea coast in Mecklenburg-Western Pomerania, a federal state in Germany, the significance of coastal protection is expected to grow in the coming years as sea level rise is thought to increasingly threaten coastal communities (Vousdoukas et al. 2017). To address this, new coastal protection measures will be implemented, and existing ones will be maintained. For this doctoral thesis, three sites were selected to study ecological changes around each of the most commonly used coastal protection measures (Fig. 8). The chosen study sites were Graal Müritz (groynes), Ahrenshoop (sand nourishments) and Thiessow (breakwaters and revetments).

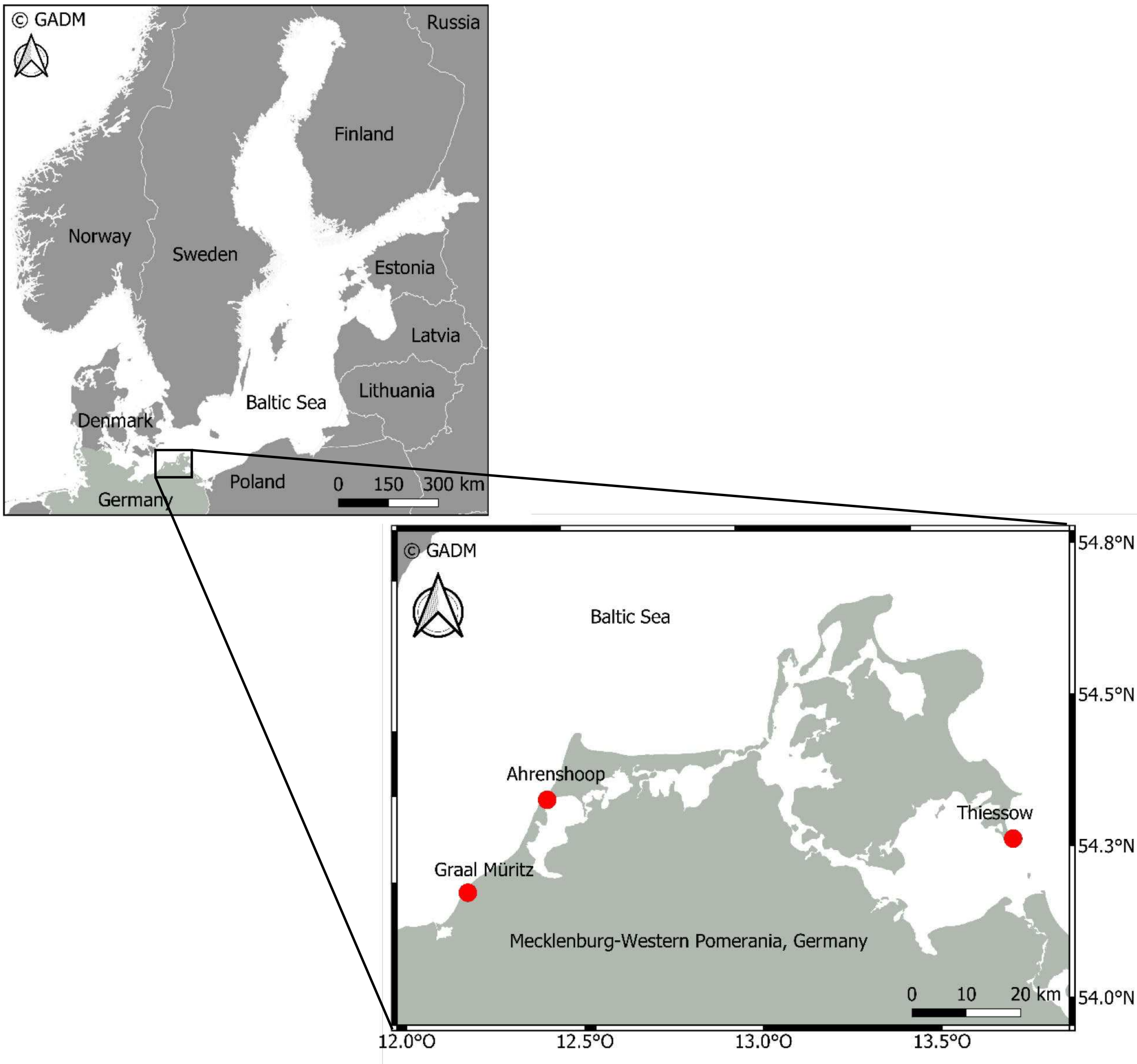

Figure 8: Overview of the three major sampling sites in Mecklenburg-Western Pomerania, Germany. Map data: © 2024 GADM (Database of Global Administrative Areas).

Graal Müritz. This study site (54°15’34.412” N, 12°14’30.692” E) is protected by 38 single-row wooden groynes installed perpendicular to the beach (Fig. 9). They were first installed in 2002 and 2005, and since then replaced as needed to maintain coastal stability. Until the 1960s, a revetment consisting of large stones was used to protect the coast. Later, this hard coastal protection measure was intentionally covered by sand and forms the present coastal protection dune. Until 2003, sand nourishments were used to strengthen this dune too (MLUV MV 2009). Behind the groynes, sandy beaches and dunes continue towards the municipality. The coast opens directly into the Baltic Sea with a north-west orientation. As Graal Müritz is located at the compensation coast, the sediment is therefore transported by currents from the south-west to the north-east. The area is highly influenced by human activity. At the municipality border of Graal Müritz, up to a nature reserve, an unprotected beach is located. The control site was placed here, at least 1.5 km from the last row of groynes.

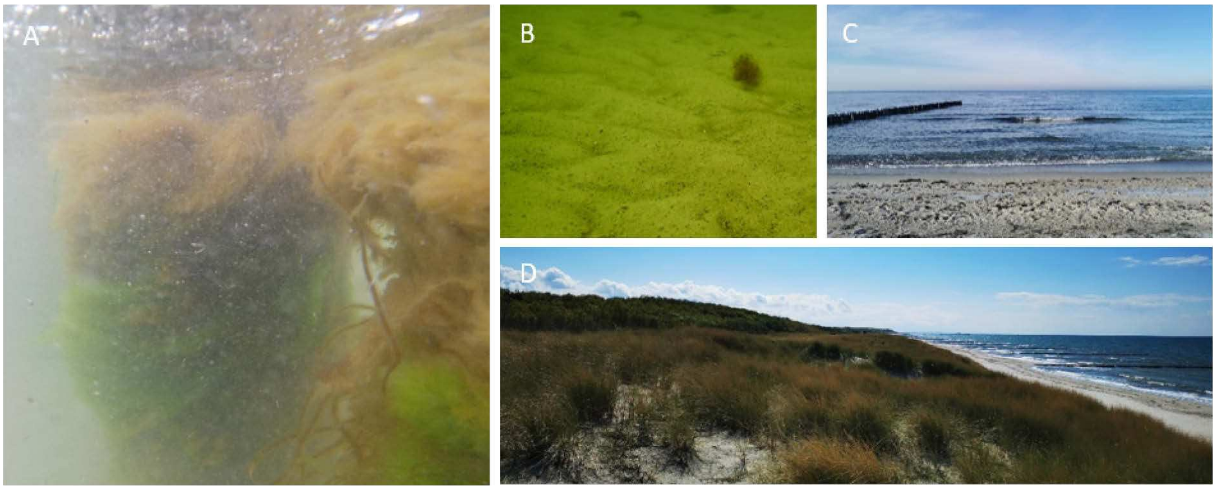

Figure 9 (A – D): Impressions of the sampling site in Graal Müritz. (A) shows the wooden groynes covered by macrophytes in the summer, (B) the sandy sea bottom near the groynes with drift algae but no permanent or seasonal vegetation, (C) the mostly unvegetated beach area and (D) the vegetation on white and grey dune. Not shown is the control site located 1.5 km to the north-east.

Ahrenshoop. Located 15 km towards the north-east from Graal Müritz, the municipality Ahrenshoop (54°22’50.573’’ N 12°25’16.506’’ E) faces the Baltic Sea with a similar orientation. Again, tourism is the main industry in this region, especially in the summer season. Coastal protection structures has been in place since the 1950s, including 64 rows of wooden and double-row box groynes with concrete fascines, similar to Graal Müritz (Fig. 10). But additionally, regular sand nourishments every 5 - 7 years are performed there (MLUV MV

2009). The sand nourishments cover the beach, as well as part of the dune, to strengthen and enforce the protective nature of the structure, but also reach into the shallow water. The sand for this nourishment is extracted from nearby donor sites. After the nourishment, the dune was replanted with *Ammophila arenaria* (L.) Link for stabilization purposes. Similar to Graal Müritz, the alongshore sand transport dominates the region. Despite the coastal protection measures, the coastal recession rate still varies around 0.2 – 1.0 m per year (MLUV MV 2009). The sampling for this dissertation focused on spatial and temporal comparisons of the nourished area, with samples taken every few weeks to months. Due to immediate human impact during nourishment, an additional sample site was chosen to observe natural disturbances, like storm events, enabling a comparison between anthropogenic and natural influences. This included water sampling from the sea bridge in Wustrow (54°21'09.6" N 12°22'59.8" E) which is located at least 3 km southwest from Ahrenshoop.

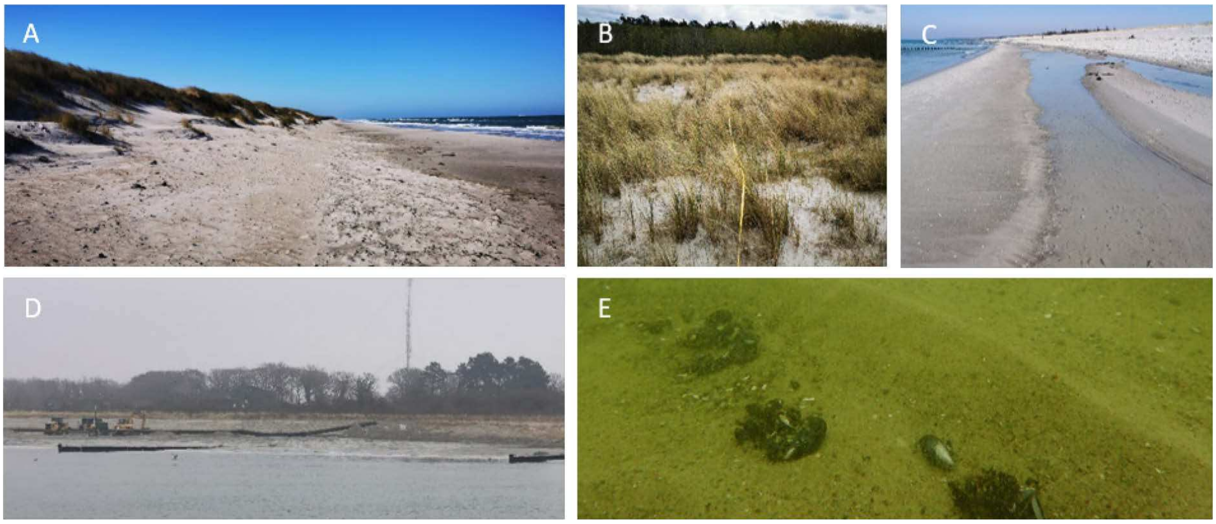

Figure 10 (A – E): Impressions of the sampling site in Ahrenshoop. (A) is the beach area before the sand nourishment with primary dunes, (B) the vegetation on the white dune before the nourishment, (C) the beach area one week after the nourishment with large pools of water due to the nourishment, (D) impression of the procedure of the sand nourishment in winter 2021/2022 and (E) the sandy and unvegetated sea bottom in the area with mussel shells.

Thiessow. The municipality Thiessow (54°16'21.4"N 13°42'17.4"E) is located in the south-east of the island Rügen. Unlike the other sites, it faces the Greifswalder Bodden rather than the open Baltic Sea. The area features sandy beaches and coastal forests influenced by human infrastructure such as walkways (Fig. 11). Coastal protection measures date back to the late 19th century when dikes and revetments were installed after heavy flooding of the region. In

1990/1991, the revetment at the study site was reinforced as a coastal protection measure with a length of more than 50 m. Next to that coastal area, a system of five breakwaters with a total length of more than 400 m was installed in 1992 (MLUV MV 2009).

Figure 11 (A – D): Impressions of the sampling site in Thiessow. (A) shows the stone revetment covering the coastline into the shallow water, (B) the mostly submerged breakwaters with a distance of 80 m to the beach, (C) the fully vegetated dune in front of the breakwater and (D) the control dune without any coastal protection.

6 Methodological approach in the dissertation

The main goal of the thesis is to evaluate habitat changes caused by various coastal protection measures. Accordingly, the methods used to assess these changes must meet certain criteria: all methods must be feasible and applicable across diverse conditions, both onshore and underwater, even with limited visibility, and versatile enough to capture different levels of habitat change. These methods focus on biodiversity-related topics, including vegetation, sediment, turbidity and nutrients analysis. The emphasis is on recording the outcomes of habitat changes rather than on altered dynamics driving them. The methods in this dissertation follow the specific workflows illustrated here.

Sediment cores. The samples were collected for sediment characteristic analysis (Fig. 12), including determination of grain size (Schlungbaum 1979), sorting (Sindowski 1938), water content (Schlungbaum 1979), organic content and carbonate content (Czensny 1961). Pore water was extracted for nutrient analysis from the same cores. Mixed sediment samples were collected from the first 20 cm of sediment across dune, beach and the seafloor in the shallow water (up to 3 m water depth). A subsample (5 mL) was processed to determine water content (dried for 4 h at 105 °C), organic content (incinerated for 4 h at 550 °C) and carbonate content (incinerated for 6 h at 900 °C). Additionally, a 100 g subsample was sieved to assess the grain size distribution and perform a sorting analysis (mesh sizes of the sieves: 2 mm, 1 mm, 0.7 mm, 0.5 mm, 0.2 mm, 0.1 mm and 0.063 mm). Pore water was extracted from the remaining sample for measurements of nutrient concentrations (nitrate NO_3^-, nitrite NO_2^-, ammonia NH_4^+ and phosphate PO_4^{3-}).

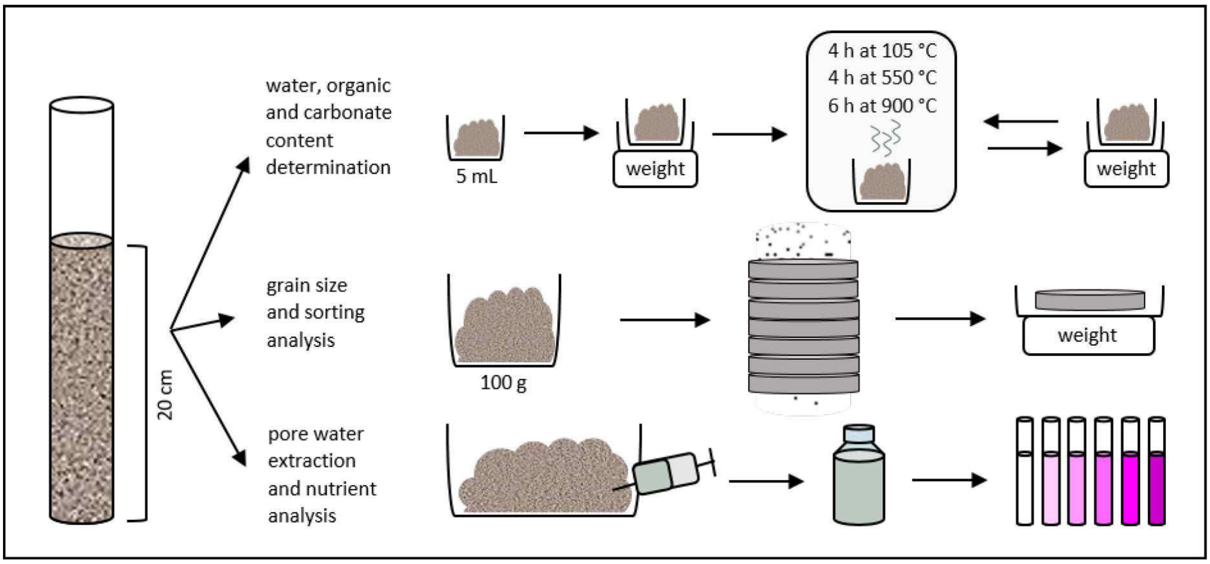

Figure 12: Workflow of the sediment analysis performed in the dissertation. The first 20 cm of the sediment was extracted via a sediment core and the sediment mixed. One subsample (5 mL) was used for the water, organic and carbonate content determination and another subsample (100 g) for grain size and sorting analysis. Pore water was extracted from the remaining sample for nutrient analysis.

Water samples. The samples for nutrient and suspended solids analysis were collected by hand with a water sampler from the research vessel LIMANDA or a sea bridge up to 3 m water depth. All other samples were taken by divers, again, up to 3 m water depth. The water samples were filtered using 0.45 µm pore-size glass fibre filters (Fig. 13). For suspended solids analysis, this filter was weighed beforehand, then dried for 4 h at 105 °C after filtration and weighed again. To measure the portion of organic solid particles, the filter was incinerated at 550 °C and weighed again. Nutrient concentrations (nitrate NO_3^-, nitrite NO_2^-, ammonia NH_4^+ and phosphate PO_4^{3-}) were analysed in the filtered water.

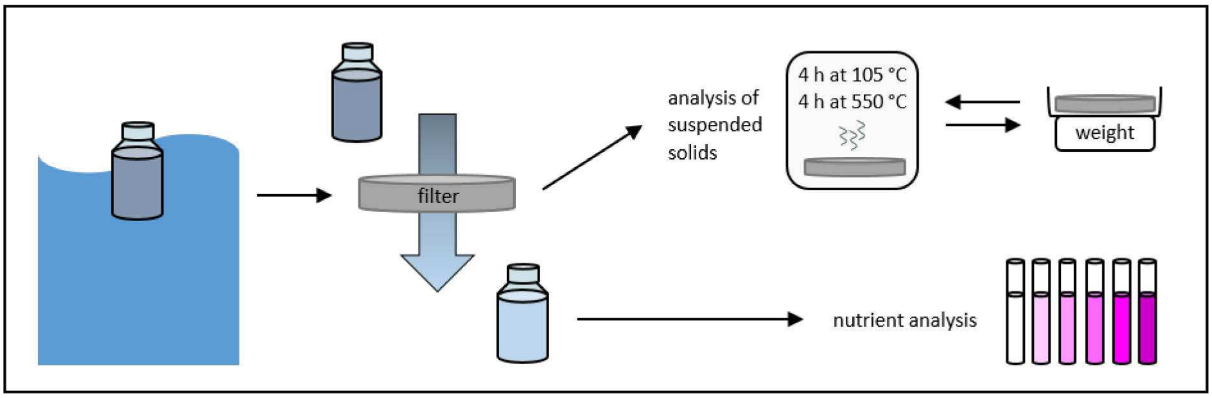

Figure 13: Workflow of the water analysis performed in the dissertation. The sample was taken by hand either with a water sampler or by divers. The samples were filtered and the filter was weighed to determine the amount of solid particles in the water. The filtered water was used for nutrient analysis.

Vegetation data. The data were recorded across dunes, beaches and underwater habitats (Fig. 14). In the terrestrial habitats, data on abundance and coverage were collected along belt transects from the waterline to the end of the grey dune, using the modified Braun-Blanquet scale (Braun-Blanquet 1964, Ellenberg 1992). Underwater, qualitative samples of algae were collected either from sandy substrates or scraped from hard substrates at three water depths (0.5 m, 1.5 m and 3 m).

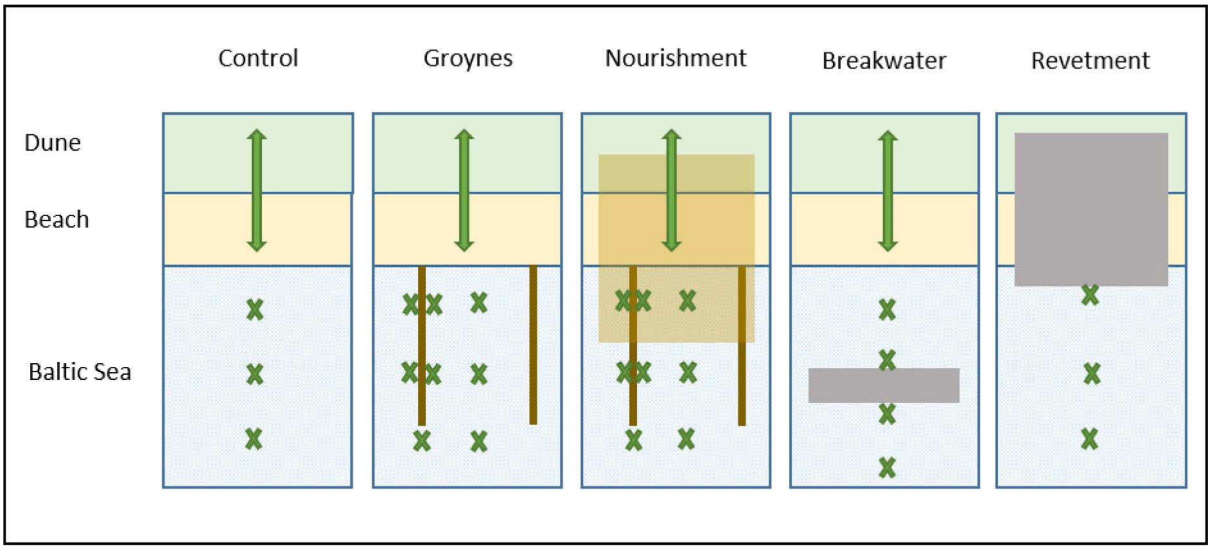

Figure 14: Schematic of the sampling design for vegetation data. Green signs (x or arrows) mark the positions of sampling as seen from above. The vegetation data was recorded on the terrestrial habitats (dune and beach) using abundance and coverage estimations. In the aquatic habitats, qualitative algae and plant samplings were performed.

In the following sections, the ecological consequences of different coastal protection structures are discussed. This includes the effects on the various coastal ecosystems as well as the spatial and temporal extent of the measures at the German Baltic Sea coast that were analysed for this dissertation, namely groynes, sand nourishments, breakwaters and revetments.

7 Conventional structures: groynes, breakwaters and revetment

The first category of coastal protection measures investigated in this work were the conventional structures, in this case groynes, breakwater and revetments, in **publication II** (Glueck et al. 2024), **publication III** (Glueck et al. 2025) and **publication IV** (Glueck and Schubert 2025). All these structures have measurable effects on their surrounding habitats in the areas studied for this dissertation, in both terrestrial and aquatic ecosystems. Ecological consequences are changes in sediment characteristics, with the changes being more pronounced in close proximity to the structure, or alterations in the vegetation composition. The respective findings for groynes are described in Glueck et al. (2024) and Glueck and Schubert (2025), the data for breakwaters and revetments in Glueck et al. (2025).

Sediment conditions of coastal areas are determined by several factors, including wave climate, sediment influx, sea level and human activity (Hegde et al. 2021). Sediment accumulating on the land is further influenced by wind, rain and vegetation and other factors (Davidson-Arnott 2010). Alterations in these factors can lead to changes in sediment conditions. Important characteristics to estimate sediment conditions are grain size, sorting grade, pore water, organic content and carbonate content.

Changes in sediment conditions were recorded in areas with breakwaters and revetments (Glueck et al. 2025), though, these changes are quite different from each other. This results in contrasting conditions near the coastal protection structures: breakwaters lead to an increase of the organic content in the shallow water zone protected by the structure itself and, at the same time, smaller grain sizes were recorded in this zone (Glueck et al. 2025). These changes are mostly related to the modified hydrodynamic patterns in front of the breakwater with reduced wave energy and currents (Martin et al. 2005) and match previous findings (Airoldi et al. 2005, Moschella et al. 2005, Rosenberg 1995). Revetments also have a strong influence on the shallow water zone, although the changes occurring here are in contrast to those reported near the breakwaters: the grain size measured in front of the revetment increased and no accumulation of organic content was recorded in this area (Glueck et al. 2025). These changes are, again, the results of the hydrodynamic conditions in front of the coastal protection structure (Ariffin et al. 2018, Chapman and Underwood 2011). At this point, it is very important to add, that the impact of hard coastal protection structure is especially great when they are placed in areas where soft sediment dominates (Nordstrom 2000). This was the case in the study region Thiessow where only sandy sediments were reported and hard substrate is otherwise limited - besides the coastal protection structures themselves (Glueck et al. 2025).

Although an impact of the coastal protection structures on the grain size and sorting of the sediment in the aquatic zones near the structures was reported, this was not the case in terrestrial ecosystems (Glueck et al. 2025). The analysis showed that the sediment composition of sites with breakwaters and groynes and control sites without coastal protection measures are almost identical. Nevertheless, sediment changes were observed, including a significant increase in water content and lower nutrient concentrations at the breakwater beach, while water content was significantly lower and nutrient concentrations higher at the dune (Glueck et al. 2025). A similar nutrient concentration pattern was reported at the coastal area protected by groynes, although overall slightly lower nutrient concentrations were measured there (Glueck et al. 2024).

These changes in sediment characteristics have an impact on other ecosystem parameters, such as the vegetation near the coastal protection structures. Three different effects on the biodiversity in coastal ecosystems after the introduction of hard substrates were observed at the study sites: first, the hard structures led to an increase of the biodiversity underwater through an increase of macroalgae settlement (Glueck et al. 2025). Second, the plant species composition near those hard substrates changed towards more rural species (Glueck et al. 2024, Glueck et al. 2025) and third, previously at the site existing ecosystems suffered immense biodiversity loss due to coverage (Glueck et al. 2025).

The first of these observed effects, an increase in underwater biodiversity through enhanced macroalgae settlement, was reported at sites with breakwaters and revetments (Glueck et al. 2025). This also applies to coastal sites with groynes, even though biodiversity has not been determined for the habitat in this dissertation but noted during field work. Hard structures in coastal ecosystems provide substrate for a wide variety of organisms (Moschella et al. 2005). When the hard structures are placed in an ecosystem dominated by sandy, mobile sediments, this leads to a significant change in the underwater vegetation and an increase in biodiversity (Airoldi et al. 2005, Martin et al. 2005). Hard substrates introduced into coastal ecosystems for coastal protection offer a habitat for macroalgae settlement (Airoldi et al. 2005, Martin et al. 2005, Moschella et al. 2005). This is also the case in Thiessow where an overall increase in macrophyte diversity both at breakwaters and the revetment was reported (Glueck et al. 2025). Due to the desired effect of the breakwater, namely influencing the hydrodynamic situation near the coast, the composition of macroalgae differed between the side of the structure facing the beach and the side facing the sea (Glueck et al. 2025). The increase in biodiversity was especially high since the area is otherwise dominated by sandy sediment and hard substrates are missing besides scattered boulders and mussel shells.

The second effect of the hard coastal protection structures, which is a change of vegetation composition towards more rural species, was recorded on dunes and beaches of the sites Graal Müritz and Thiessow (Glueck et al. 2024, Glueck et al. 2025). Ecosystems have their own repertoire of plant, moss and lichen species that are characteristic for the habitat conditions.

When the habitat conditions change, this is reflected in the composition of species. This was reported in several studies highlighting the dependence of plant communities or plant growth on sediment characteristics such as water content and nutrient concentration in pore water (European Commission 2004, Martin et al. 2005, Van Wijnen and Bakker 1999). More possible drivers causing either the introduction of new species or the displacement of old species are sedimentation, causing the burial of slow-growing species, or erosion, which only plants with a well-developed root system can withstand (Greipsson and Davy 1997). It is therefore safe to say that the vegetation composition on the dune, which is highly adapted to the difficult habitat conditions, is an indicator for habitat conditions and their changes. Therefore, the recording of vegetation data supports the analysis of environmental changes and can display them appropriately.

The dunes and beaches in Graal Müritz and Thiessow with coastal protection structures showed changes in their vegetation composition when compared to coastal stretches without any coastal protection structures. Groynes installed at the coast led to an additional stabilization of the dune habitats (Glueck et al. 2024), although these structures are installed in the shallow water and not on the beach or dune itself. This resulted in a dense vegetation consisting mostly of species that prefer fixed dunes and are most commonly found on late dune successions. Late successional dunes show a higher diversity of moss and lichen species, but also heath and shrub species can be expected and a decrease of marram grass *Ammophila arenaria* (L.) Link at the same time. The beach near the breakwaters in Thiessow showed changes in the vegetation composition too (Glueck et al. 2025). As this coastal protection structure is placed in the shallow water in front of the beach and dune as well, the alterations were very similar to the ones recorded at the groyne site. Near the breakwater, again, both beach and dune showed a vegetation composition more similar to late dune succession. While typical dune plants were still dominating the habitat, more ruderal plants that profit from high nutrient levels and stable conditions were recorded. In summary, it can be said that groynes and breakwaters lead to a changes in species composition but not necessarily to a reduction in the overall biodiversity.

This pattern of change can also be observed on other coastlines. On Hiddensee, too, increased coastal protection in the second half of the 20th century led to a reduction of active white dunes in the area. This also affected pioneer vegetation, indicating a stabilization of the coastal sites to older vegetation units (Remke and Blindow 2011). In the Mediterranean region, changes in the composition of vegetation in the vicinity of anthropogenic structures in coastal areas are characterized by greater richness and diversity, but at the expense of a lower naturalness, e.g. by establishment of alien species with a sometimes high invasive potential (Enríquez de Salamanca 2022). At the Atlantic Sea coast, infrastructure lead to an overall shift in plant community composition, accompanied sometimes by greater species richness, diversity and coverage (Lucrezi et al. 2014) and seawalls promoted stable-dune species (Nordstrom et al. 2018).

The third effect of the conventional structures is an immediate effect on the biodiversity which arises instantly after installation of the measure and not in the course of the next few years due to changed site conditions. This is the coverage of existing ecosystems and therefore immense biodiversity loss. This happens also after the installation of revetments at the coast (Glueck et al. 2025). The structures cover both beach and dune habitats and thus cause a significant reduction in biodiversity. Only organisms that can survive growing on hard substrate, e.g. lichen and moss species, can contribute to the biodiversity of the new ecosystem. A negative effect may also apply to the underwater vegetation as both revetment and breakwater are built in the shallow water. On the sandy coast of the German Baltic Sea, mainly seagrass meadows would be affected. Building a breakwater on an existing meadow could permanently damage it, however, altered hydrodynamic or sediment conditions could threaten seagrass meadows too (Smith et al. 2009). This would first need to be investigated through further studies.

While potential impacts highlight the challenges of conventional hard structures, it is important to also examine the ecological consequences of nature-based measures, which have been increasingly applied as coastal protection strategies.

8 Nature-based measures: sand nourishments

The second category of coastal protection measures investigated in this work were the nature-based structures, namely sand nourishments, in **publication I** (Glueck 2023), **publication II** (Glueck et al. 2024) and **publication IV** (Glueck and Schubert 2025). The sand nourishment in Ahrenshoop caused both short-term consequences, a turbidity plume and changes in sediment characteristics (Glueck 2023, Glueck and Schubert 2025), as well as long-term consequences in the vegetation composition (Glueck et al. 2024) due to repeated setbacks of the dune succession.

Sand nourishments involve the deliberate deposition of large quantities of sediment in the foreshore area, on the beach and across dunes. The goal is to achieve a specific coastal profile, including a desired slope, surface area or cross-sectional shape (MLUV MV 2009). This method is typically carried out over a few weeks or months and is repeated every few years (Kortekaas et al. 2010). Unlike conventional coastal protection measures, sand nourishments do not introduce new hard structures in the area, but rather maintain the existing coastal features, e.g. wide sandy beaches and flat dune slopes. A great deal of effort is made to ensure that the extracted sediment closely matches the natural sediment on the beach and dune (van Duin et al. 2004). Therefore, no significant differences were measured concerning mean grain size and sorting grade at the nourished site in Ahrenshoop before and after the sand nourishment (Glueck and Schubert 2025). This match of sediment grain size is crucial for the longevity and stability of the coastal system, as well as for supporting the dune succession which serves as the primary coastal protection measure in this area (Jackson et al. 2010, Pupienis et al. 2014, Zelo et al. 2000). The longevity of nourishments can be further enhanced by incorporating additional stabilizing coastal protection measures, e.g. groynes or breakwaters (Colosio et al. 2007). This was evident in Ahrenshoop, where the presence of groynes extended the intervals between nourishment events to at least five years (MLUV MV 2009). In contrast, a misfit of the main characteristics of the nourished sediment can result in changes in morphodynamics in the coastal region (McLachlan 1996) or a reduced effectiveness and longevity of the nourishment (Eitner 1996, van Duin et al. 2004).

Some effects of the sand nourishment cannot even be prevented by careful selection of the nourished sediments. Glueck and Schubert (2025) showed that this includes an increase of the water content and the decrease of the organic content within the sediment at the nourished site. Both changes are directly linked to the nourishment process itself: when the sediment is collected from the seabed, a large proportion of the organic matter is washed out. To transport the sediment to the beach, it is mixed with water in a ratio of 1:2 and washed ashore using long pipe systems. This process brings large quantities of water to the beach, and above all, sediment that is low in organic matter. Similar effects have been observed in other sand nourishment projects using technically related methods, suggesting that most nourished coastal sections are likely subject to these recurring changes (Colosio et al. 2007, Tauran et al. 2025). However, within a few months, microbial and macrobial processes contribute to an increase in organic content in the sediment: the sandy beach meiofauna was significantly impacted right after the nourishment showing a sharp decline in total abundance and changes in community composition, but recovered within six months after the nourishment (Kapshyna et al. 2024). Other studies showed communities dominated by a few species able to avoid burial and suffocation (Targusi et al. 2019) or to rapidly recolonize (Tauran et al. 2025). Particularly in shallow waters, currents and wave action can accelerate a recovery of benthic meiofauna (Schlacher et al. 2012). Therefore, changes in meiofauna could only be measured over a short period of time.

In addition to water and sediment, sand nourishments introduce nutrients into the system because sediments are sourced from deeper layers from the Baltic Sea. This results in an increase of nitrate, nitrite, ammonia and phosphate concentration in the pore water at the nourishment site (Glueck et al. 2024) and in the water column (Glueck 2023). As nutrient sources in the dune and beach ecosystem are otherwise limited, consisting of sea spray (Holton 1980) and beach wrack (Colombini and Chelazzi 2003) among others, this increase in nutrient availability after the sand nourishment can cause changes in the natural succession of these ecosystems. The influence of artificial and natural fertilization of sandy grasslands and dunes has only been studied in isolated cases so far. However, these indicate an influence of the additional nutrients on the biodiversity of the areas: the increased soil fertility negatively correlated to plant diversity (Day et al. 2004, Jones et al. 2004, Zemunik et al. 2016).

There are more factors connected to the sand nourishment which were influencing the succession of the coastal ecosystem: first, the existing vegetation on beach and dune was completely buried by the deposited sand. Second, after the sand nourishment, the area was replanted exclusively by marram grass *Ammophila arenaria* (L.) Link. And third, the repeated application of sand nourishment every few years disrupted the natural dune succession, leading to the gradual formation of altered plant communities over time.

The first mechanism, burial by sand, impacts the dune only in the short term as both a manual recolonization of the dune is performed within weeks after the nourishment and pioneer species return quickly (Glueck et al. 2024). However, the second mechanism has longer lasting effects, as the replanted marram grass *Ammophila arenaria* (L.) Link persists on the dune and plays a crucial role in restoring key ecosystem functions, such as sediment stabilization (Kiehl and Kollmann 2019). Nevertheless, since only one plant species was actively replanted in the area, biodiversity on the beach and dune initially declined. Other plant species began to return within one year, but species richness remained lower compared to an unnourished dune (Glueck et al. 2024). The third mechanism primarily affected the long-term development of the dune. Repeated nourishments causing altered sediment conditions (Glueck and Schubert 2025) and periodic increases in pore water nutrient concentration (Glueck et al. 2024) covering larger areas of the dune significantly impact dune succession. As a result, the vegetation community shifts towards species adapted to unstable conditions, favouring species that can either withstand the nourishment process or recolonize the nourished zone quickly.

This transition occurs at the expense of less competitive plant species. Among the most affected organisms are lichens. No lichen species were recorded at the sand nourishment site, even before the sand nourishment. This indicates that their habitat-specific requirements are not met anymore at the nourishment site (Kammann et al. 2022). Multiple species were found on other dunes in the same region (Glueck et al. 2024). It should also be noted that the sand nourishment did not only impact the areas where sand was deposited (foreshore, beach and white dune) but also affected neighbouring ecosystems, such as grey dunes. There, a shift in vegetation composition and biodiversity was observed as well (Glueck et al. 2024).

In Ahrenshoop, no effects were recorded in the aquatic part of the system. Even though parts of the groynes were partially covered by the sand nourishment, more than half of the groynes remained submerged and were covered by macroalgae throughout the years. Nevertheless, previous studies suggest that sand nourishments can impact macrophyte communities (Manzanera et al. 2011). Elevated nutrient concentrations in the seawater can favour opportunistic macroalgae as described by Morand and Briand (1996): the excessive growth of macroalgae is a response to a supply of nutrients and rapid growth rates were recorded at the temperature ranging from 10 to 20 °C (Taylor et al. 2001). As the sand nourishment in Ahrenshoop was performed during the winter, the low water temperature might have inhibited excessive macroalgae growth here.

Besides additional nutrients, suspended sediments are flushed into the Baltic Sea at the nourishment site, causing a turbidity plume near shore which can persist for three months (Glueck 2023, Manning et al. 2014, Nordstrom et al. 2004, Roegner et al. 2021). This plume is not confined to the nourishing site, but can be detected up to 400 m away offshore. Analysis of suspended solids from the water column revealed that it does not contain significant amounts of organic material, as had been measured at the extraction site beforehand. Furthermore, no notable accumulation of organic material was observed on the beach or dunes following the nourishment (Glueck and Schubert 2025). This raises concerns that at the extraction site, a separate turbidity plume - primarily consisting of organic material washed out of the sediment - may develop instead (Capello et al. 2014).

Turbidity plumes can also be caused by natural occurring disturbances. Wind (Jordan et al. 2010) and waves (Capello et al. 2014, You 2005) are the main drivers of turbidity in shallow waters, leading to sediment suspension and the formation of turbidity plumes. This can impact the light penetration into the water column. Since plants and algae rely on light for photosynthesis, the depth to which light penetrates into the aquatic system is critical for their distribution. Seagrass, for instance, is a well-known species whose distribution was and is severely restricted by this, requiring a minimum of 11 % of the surface irradiance (Duarte 1991). An increased turbidity over a longer period can also affect other organisms living in that area. For example, the negative influence on growth and abundance of invertebrates is already reported (Manning et al. 2014, Roegner et al. 2021). Particularly large plumes have been recorded during and after storm events, especially near recently nourished coastal stretches (Jackson et al. 2010, Nordstrom et al. 2004, Wilber et al. 2006). However, during the sand nourishment, the concentration of suspended solids in the water column was almost twice as high as during the storm events (Glueck 2023). Additionally, the turbidity plume persisted for a much longer period - over three months - while the turbidity plume of the storm events persisted for only several days. Nevertheless, the impact of elevated wave energy and overall different hydrodynamic conditions due to a storm can affect underwater vegetation too (Bučas et al. 2007, Reusch and Chapman 1995).

9 Conclusion

Against the background of climate change, increasing sea level and risk of flooding, the demand for coastal protection measures is rising (Airoldi et al. 2005). The results of these studies contribute significantly to a better understanding of the strategies often used, to assessing their impact and to identifying possible gaps in terms of environmental compatibility.

Conventional coastal protection structures such as groynes, breakwaters and revetments can cause long term habitat destruction, changes in sediment conditions and shifts in vegetation communities. Biodiversity responses vary: hard substrates increase underwater biodiversity by promoting macroalgae growth, but possibly harm seagrass meadows. On land, the structures lead to shifts in plant species towards late-dune successions. At the same time, the interest in nature-based coastal protection measures is increasing, such as sand nourishments. However, even these measures cannot be implemented without consequences. Sand nourishments deposit large amounts of sediment on beaches, dunes and in the shallow water, and this technique is causing turbidity plumes and alterations in sediment characteristics and nutrient levels. Biodiversity declines long-term as buried vegetation is replaced by single-species replanting, altering dune succession and favouring disturbance-tolerant species. Compared to storm-induced turbidity, sand nourishments cause higher suspended sediment levels and prolonged nutrient release, potentially further impacting aquatic ecosystems.

Still, some aspects of the ecological impacts of coastal protection measures remain unknown and more research is needed before all processes, biogeochemical and hydrodynamic, are thoroughly investigated. Examples of previously unexplored topics are the fate of nutrients introduced into ecosystems by coastal protection measures, but also the long-term monitoring of affected areas. Fortunately, in view of the significant impact of anthropogenic structures on coastal ecosystems, understanding the diversity of organisms and the associated functioning of ecosystems has gained political and scientific importance. This has led to nature-based coastal protection measures being often presented as nature-based solutions to these problems, but in many cases, they are merely a compromise between technical interventions and ecological approaches. This is confirmed by the results of this dissertation, which show that such measures, namely sand nourishments, remain fundamentally technical interventions which cause a wide range of ecological impacts to coastal ecosystems. Genuine natural coastal protection structures include ecosystems such as kelp forests, seagrass beds, mangroves, salt marshes, coral and bivalve reefs, which provide coastal protection while enhancing biodiversity and ecosystem functions. For the German Baltic Sea coast, seagrass meadows and wetlands are the most important and, above all, applicable measures. However, in the Baltic Sea, these methods are mainly used in isolated cases: as part of research or pilot projects, although they offer great opportunities for coastal protection (Kiesel et al. 2023, Schernewski et al. 2022). Nevertheless, there is still room for improvement in the currently used nature-based coastal protection methods, which are already being tested on a small scale. For example, the cooperation with the coastal protection authorities during the sand nourishments for this thesis led to the initiation of various scientific experiments dealing with the biodiversity and stability of the plant vegetation communities on the coastal dunes. This includes the use of modern monitoring systems with drones and planting trials of other dune plants than usually. This shows that the current methods in coastal protection do indeed follow a dynamic revision concept and that scientific findings help to ensure that improvements can be implemented effectively.

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Part II: Publications

Publication I: Comparison of high turbidity events: Sand nourishments and storm events on sandy beaches at the Baltic Sea, Germany

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Comparison of high turbidity events: Sand nourishments and storm events on sandy beaches at the Baltic Sea, Germany

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ABSTRACT

Coastal zones are permanently under stress by storms, cliff breaks, waves and currents. These events can cause the retreat of the coastline and are currently compensated by beach nourishments. The commonality of these sediment eroding and accumulating processes are turbidity plumes created in coastal waters, increasing the resuspension of particles and possibly nutrient concentrations. To compare sand nourishments and storm events, total suspended solids (TSS) and nutrient measurements were performed during winter season at the German Baltic Sea Coast. A pre-experiment showed that the TSS was homogenous through the water column. There were significant differences between both events, with sand nourishments exceeding the TSS of storms with the factor two. Due to the nourishment mechanism, the relative organic content was lower than during storm events. The nutrient uptake was unsteady. Therefore, sand nourishment can be considered to have more influence on the ecology of sand shores than storm events.

1. Introduction

Coastal zones are highly dynamic ecosystems constantly changing due to the exposure to different environmental forces, such as wind and waves. There are multiple natural events that can cause substantial modifications of these ecosystems, e.g. storm events and cliff breaks (Jarmalavičius et al., 2016; Sterr, 1989). Cliff breaks are immediate, rapid changes in the coastal morphology but also waves promote changes directly through overwashing, flooding and wave induced currents that transport sediments (Mattheus and Diggins, 2019). Both of these modifications of the sediment budget can be in a dynamic equilibrium. Cliff breaks on steep coasts as well as rivers (Salmela et al., 2020; Siegel et al., 1999) are ensuring the constant supply of sediment to the shores and storm events transport these sediment along the shore (Tõnisson et al., 2014). But they can also be unbalanced and beach morphology changes cause a permanent coastal retreat.

In both scenarios, natural storm events can cause major erosion on the coast (Labuz and Kowalewska-Kalkowska, 2011). Sediment is produced by cliff breaks during storms and washed onshore by waves (Davidson-Arnott et al., 2019). This provides adjacent shores with sediment and although coastal recession is thus created on cliffs, the coastline on sandy beaches can be stabilized. But if the sediment supply by cliff breaks is missing or the sediment transport along the coast is inhibited by anthropogenic constructions, this can result in a retreat of the coastline on sandy shores (Furmanczyk et al., 2011; Orviku et al., 2009). Since many cliffs at the coast are protected and cliff breaks are prevented or sediment is trapped elsewhere (Fitri et al., 2019), the natural sediment supply is decreasing and leading to a decline of sandy beaches. Due to the high wave energy during storm events, even more sediment can be transported from the beach and dune to the coastal waters accumulating and forming sand bars (Janušaitė et al., 2023). The increased erosion is therefore leading to a negative net balance of sediment on the beach and dune weakening the protection of the hinterland. This applies to the coast of the Baltic Sea in Germany (StAUN Rostock / Department Coast, 2009).

The solution to strengthen and maintain the coastline is coastal protection. There are various approaches to both weaken the sediment transport and stabilize the coast to prevent erosion, or to compensate the negative net balance of the sediment. One example for compensating erosion on sandy shores are sand nourishments. Sand nourishment are considered to be nature-based coastal protection measurements since they can mimic a natural process: They compensate the deficit of sediments due to the absence of cliff breaks or sediment traps and therefore ensure the sediment transport along the coast without causing a retreat of the shoreline. Additionally, they also dissipate wave energy decreasing the action of the waves at the beach and cliffs (Staudt et al.,

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2021; Temmerman et al., 2013).

Sand nourishment for beach reconstruction and dune stabilization have been successfully carried out for several decades (StAUN Rostock / Department Coast, 2009). This also applies for the Baltic Sea. While there have been several studies about the consequences of sand dredging activity at the dredging site (Kortekaas et al., 2010), there is still a lack of information about the nourished site.

Sediment relocation is always related to high turbidity events since the sediment components are resuspended in the water column. There are multiple approaches in measuring turbidity and sedimentation over a long period of time for monitoring or prediction of upwelling events but also to measure the natural resuspension of bottom sediments, e.g. with FerryBox Systems (Kikas and Lips, 2015; Rasmus et al., 2015). But in the Baltic Sea, the long-term sedimentation rates can be very variable and are dependent on recent events that are the drivers of the sediment relocation. Typical long-term drivers are underwater pipeline or traffic constructions and regularly dumping sites of dredged materials as these disturbances last for several years (Rasmus et al., 2015; Kikas and Lips, 2015; Lednicka et al., 2022).

But turbidity plumes can also be created by events limited in time and place. One of the drivers of high turbidity events in coastal zones are sand nourishments. It is generally agreed that the turbidity caused by a sand nourishment on the sub-aerial beach is only localized and transitory in comparison to sand nourishment actions nearshore or offshore (Roman-Sierra et al., 2011; Wilber et al., 2006). Additionally, waves have been shown as the primary cause for turbidity in the bottom near waters by resuspending sediments (Capello et al., 2014; You, 2005). This can result in even further increased local turbidity plumes during storms at recently nourished sites (Nordstrom et al., 2004). Still, these short-term effects can harm the ecology of the sea bottom (Airoldi, 2003; Rönnbäck et al., 2007; Herman et al., 2021; Jordan et al., 2010). Endangered species are macroalgae, mussels but also other mostly sessile organisms. Manning et al. (2014) and Roegner et al. (2021) also reported a negative influence on growth and abundance of invertebrates.

Generally speaking, sand nourishments and storms produce both turbidity plumes. Nevertheless, there has not yet been a comparison of both these events in the shallow water zone. Assessing the turbidity caused by beach nourishments in an ongoing nourishment and the turbidity caused by storm waves in an adjacent area can show how the mean turbidity at a mean wave regime can be changed. This would provide the opportunity to assess the impact of the nature-based coastal protection measurement in a clearer light. Therefore, we designed the following experiments to take on the main questions: Are there disparities in the turbidity (measured in total suspended solids TSS) in the water column during sand nourishments and storm events? What are the main sediment contents causing the plumes? Do sand nourishments add nutrients to the water column by introducing alien sediments to a new habitat?

2. Material & methods

2.1. Sampling stations and design

The data were collected in Ahrenshoop and Graal-Mueritz, two small cities at the Baltic Sea (Fig. 1, Ahrenshoop: 54° 22′ 50.573″ N 12° 25′ 16.506″ E and Graal-Mueritz: 54° 15′ 34.412″ N 12° 14′ 30.692″ E).

Both cities are located in a region described as the “bodden compensation coast”, consisting of different islands and spits. Higher hilltops of moraines that are enclosed by water after the last ice age are connected by narrow land bridges now. These land bridges were formed from by currents eroded material of the island cores. Backwards are almost completely from the open sea isolated waters (boddens). Most important feature of this geographical region is the particularly irregular, highly structured shape of the coast (StAUN Rostock / Department Coast, 2009; Leppäranta and Myrberg, 2009).

Flat coasts dominate the German Baltic Sea Coast, as in Graal-Mueritz and Ahrenshoop. While the sediment supply for Graal-Mueritz is ensured by sand transport from more western sections of the coast, the sediment supply for Ahrenshoop was originally ensured by cliff breaks. These cliffs are located in the 15 km coast section between the cities. Part of the cliffs are now protected with breakwaters to prevent a retreat of the coast (StAUN Rostock / Department Coast, 2009). An additional breakwater right before Ahrenshoop is used as a sediment trap to stabilize the shore but prevents the lateral sediment transport feeding the adjacent beach. Through the missing sediment supply by cliff breaks, high lateral sand transport rates weaken the protective function of the dunes in Ahrenshoop. Additionally, storm surges can threaten the city from both sides, Baltic Sea and bodden side. Therefore, sand nourishments are carried out every 5 to 10 years (Kortekaas et al., 2010). In winter 2021/2022, the nourishments consisted of almost 600 thousand cubic meters and lasted 3 months. The nourishments were performed in 3 separate steps, each step nourishing about 1.5 km of the beach and dune (Fig. 2). Every nourishment lasted about 1 month. For the nourishment, a duker was connecting the dredging vessel with the beach and the sediment was flushed through this duker to the beach. Heavy machinery on the beach was then distributing the sediment and forming the new shape and slope of dune und beach. After each nourishment, the duker was moved to the next coastal section. Therefore, the

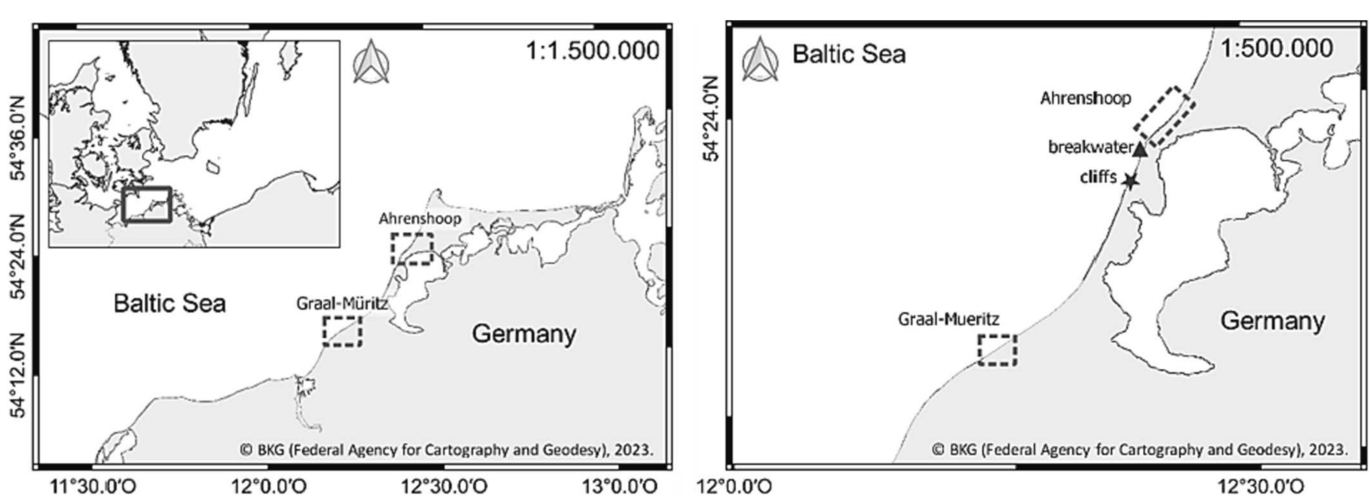

Fig. 1. Sampling sites for the (pre-) experiment were Ahrenshoop and Graal-Mueritz at the Baltic Sea, Germany. In Ahrenshoop, a nourishment took place in winter 2021/2022. In Graal-Mueritz, samples were taken during storm events in winter 2022/2023.

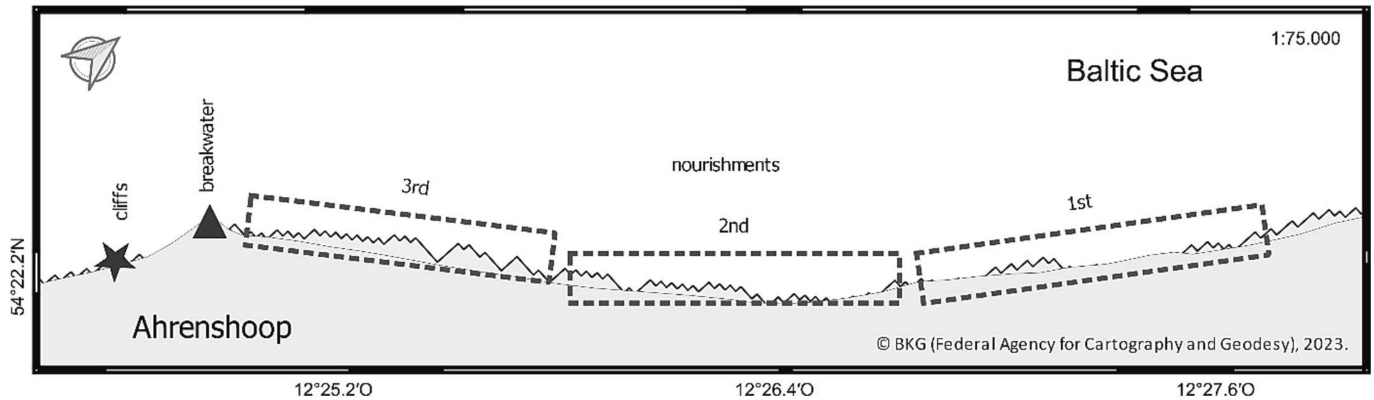

Fig. 2. Positions of the nourishments in Ahrenshoop. Each nourishment was performed at a coastal section of around 1.5 km length with a duration of about 1 month. In the south of Ahrenshoop (left side), there are cliffs and breakwaters.

water samples for the first nourishment were taken during the nourishment of the first coastal section, the samples for the second nourishment were taken during the second coastal section and the samples for the third nourishment were taken during the third and last coastal section.

Graal-Mueritz has an almost identical geographic orientation and is therefore suitable for the comparison with the nourishment in Ahrenshoop. In contrast to Ahrenshoop, is not endangered by storm floods because it is not located between two water bodies (Baltic Sea and bodden). The lateral sand transport rates are also very high but due to the larger land mass the erosion of the coastline is not comparably dangerous and the sediment supply is secured. The water samples during storm events were taken in Graal-Mueritz. The wind and wave data is from a weather station in Ahrenshoop (54° 23′ 19.741″ N 12° 25′ 54.800″ E) and was purchased for the duration of the samplings from © Windfinder.com (2023). Information about the duration, track and other characteristics of the storm events is from DWD Climate Data Center (2023).

The sampling plan consisted of taking water samples in Ahrenshoop without and during the ongoing sand nourishment. All samples during the nourishments were taken on 25th November 2021 (first nourishment), 11th January 2022 (second nourishment) and 10th February 2022 (third nourishment), see Fig. 2. The samplings without any nourishment activity or storms were taken on 14th October 2021, 24th November 2022 and 24th January 2023. In Graal-Mueritz, the samplings were performed during storm events on 03th and 20th February 2023. Both sites are subjected to the same wind and wave regime due to their neighbouring location. The distance from the sampling site to the coastline was in both sites about 200 m and the water depth was 4 m. On the nourishment site, water samples were taken from onboard the drifting research vessel "Limanda" of the University of Rostock. Due to safety reasons, the samplings during the storms were not performed onboard but from the tip of the pier in Graal-Mueritz. The pre-experiment included water samples at three different water depths (0 m, 2 m, 4 m) to determine the distribution of total suspended solids (TSS) in the water column three times during the sand nourishment (number of replicates: $n = 20$) and two times before a storm ($n = 5$). This pre-experiment should answer the question whether the sampling depth of the water samples is significantly important to the following experiment. For the final experiment, the comparison between the two sites, samples of surface water (number of replicates: $n = 5$) were sufficient. The surface samples were taken three times without any and during the nourishment and before and during two different storms. At each station water samples were collected with a water sampler. Additionally, sediment samples from the nourished beach were collected on 14th March 2023 to determine sediment characteristics of the nourished sediment ($n = 5$).

2.2. Instruments, measurements and analysis

2.2.1. Total suspended solids (TSS)

A total of 50 mL of the water samples were filtered through a glass fibre filter (47-mm diameter, nominal pore size = 0.4 μm). Then the filters were dried at 105 °C for 4 h and weighed on a Sartorius balance (accuracy ±10 μg) to obtain the sediment concentrations. The weight of the filter was used to calculate the weight of particles in the water sample which is the total suspended sediment (TSS). After that, the filters were burned at 550 °C for 4 h for ignition loss.

2.2.2. Nutrient analysis

The concentrations of selected nutrients (nitrate, nitrite, phosphate, ammonia) in each water sample were analysed using the spectrophotometric method by Lambda 2 (UV/VIS Spectrometer, Perkin Elmer) according to Grasshoff et al. (1999).

2.2.3. Sediment characteristics

Sediment cores with a diameter of 36 mm and a sampling depth of 20 cm were used to determine mean grain size (Schlungbaum, 1979), sorting grade (Sindowski, 1938), water content, organic content and carbonate content (Czensny, 1961) of the nourished sediment.

2.2.4. Statistics

For the statistical analysis we used the R statistical software Version 4.0.3. The water samples were analysed, after checking for normality and variance homogeneity, using ANOVA or Kruskal-Wallis-Test with the sampling site as factor. The additional test was necessary since requirements for ANOVA were not met at all parameters. Post hoc pairwise multiple comparisons were carried out using Dunn's Test against an alpha-level of 0.05 to identify differences between the sampling times.

3. Results

3.1. Weather data

The wind direction during the samplings at the sand nourishment and the control samplings without any storm activity was very similar (Fig. 3). The wind speed was very calm and did not exceed 6 knots. At storm events, the maximum wind speed was 22 knots. The wind direction changed from South-West to North-West.

Very similar results showed the wave data. The wave direction during all samplings was West to North-West. During the nourishments and during the samplings without any nourishment activity or storms, the maximum wave height was 0.4 m. During storm events, the maximum wave height was around 1.0 m. The wave period during nourishments was 6.28 s ± 2.38 s, during storms 4.75 s ± 0.83 s and

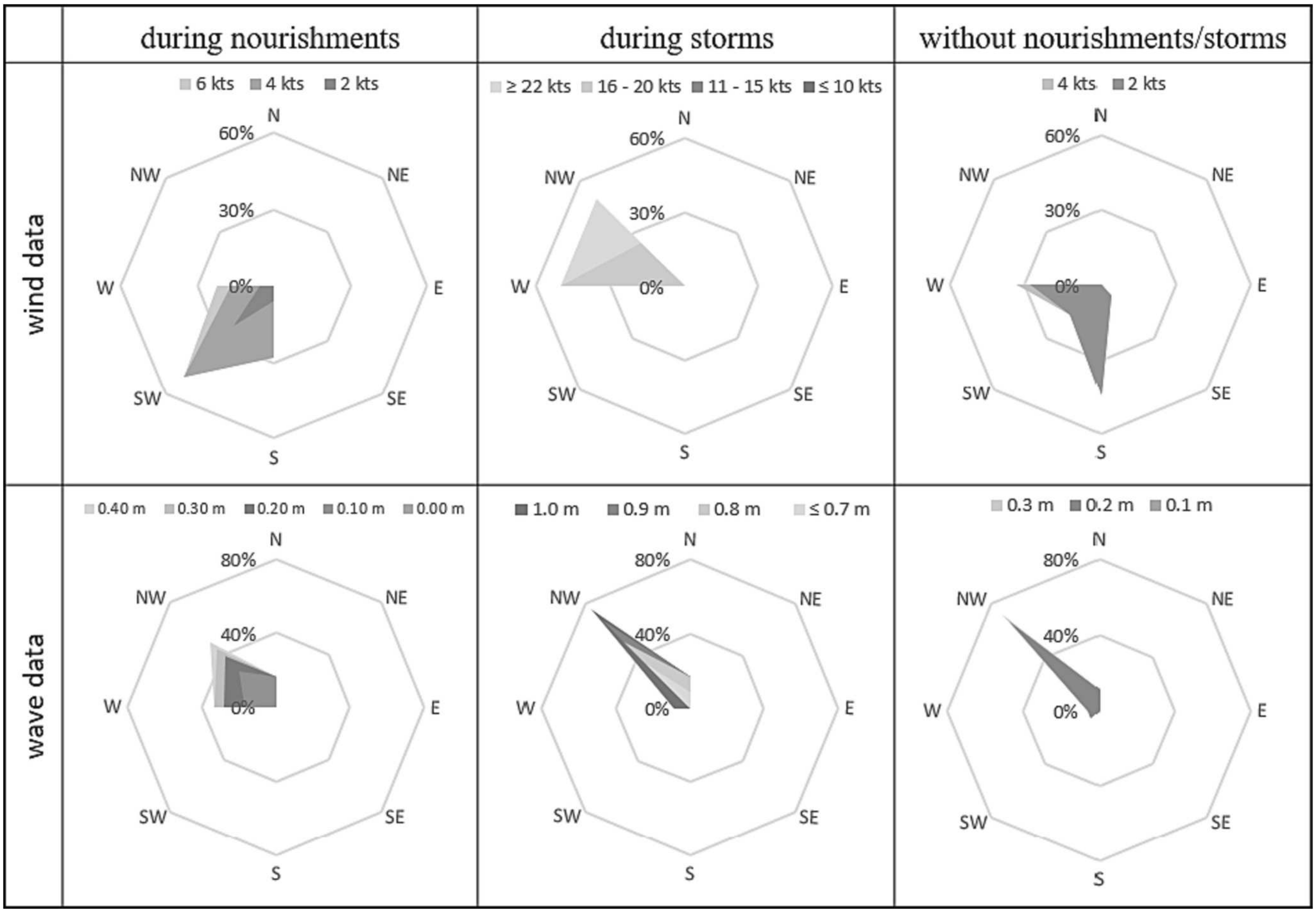

Fig. 3. Wind direction and speed as well as wave direction and height during the samplings (nourishments, storms and without any activity). The wind speed during nourishments and without nourishments/storms was very similar. The wind speed during storms was higher. The overall wind direction was similar. The wave direction was similar during all samplings. The wave height was higher during the storms.

without any nourishment activities or storms 4.22 s ± 0.71 s.

The characteristics of the first storm “Oleg” which moved from North-West to South-East across the German Coast from 30th of January until 3rd of February 2023, were a persistent strong wind with mean wind speed of 7.2–11.1 m/s. The peak velocities of the gusts reached 23.6 m/s. More than two weeks later, the two low pressure areas “Tom”

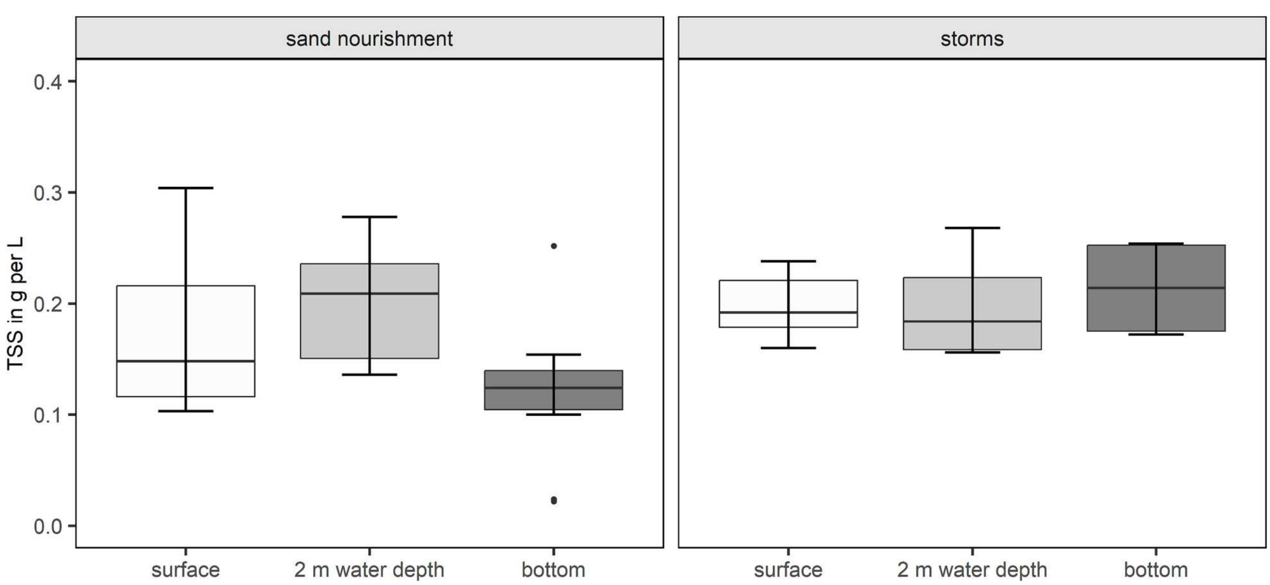

Fig. 4. Total suspended solids (TSS) concentrations in g per L at different water depths at the sampling sites before the sand nourishment and the storms. There was no activity during this sampling. Values presented by Box plots are median (middle bar), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95 % of variability) and outliers (points).

and “Ulf” coming from the same direction as before “Oleg”, again caused stormy gusts from 17th February until 21st February 2023. Maximum gust speeds around 22.8 m/s and mean wind speeds between 6.8 and 8.6 m/s were measured (DWD Climate Data Center, 2023).

3.2. Sediment characteristics

The nourished sediment had a mean grain size of 0.33 ± 0.02 mm and a sorting grade of 1.44 ± 0.13. The water content was 1.66 ± 0.42 % of wet weight and the organic content was 0.26 ± 0.14 % of dry weight. The carbonate content was 0.52 ± 0.45 % of dry weight.

3.3. Pre-experiment

There were no significant differences between the total suspended solids (TSS) concentrations at different water depths at the sampling sites without any nourishment activities or storms (Fig. 4). There were also no significant differences between the two sampling sites. All in all, the total suspended solids concentration was very similar averaging around 0.20 ± 0.04 g / L for the storm sampling site and 0.16 ± 0.07 g/L for the nourishment site.

There were significant differences in TSS between the nourishment samplings (Fig. 5). During the third sampling, a higher TSS was measured than before. The lowest TSS concentration was measured during the second sampling. But there were no significant differences between the TSS at different water depths during each nourishment sampling.

3.4. Experiment

There were significant differences between the TSS during nourishments and storms (Fig. 6; probability of error: p values <0.001 are indicated by ***, p values < 0.01 by ** and p values < 0.05 by *).

The TSS concentration was significantly higher during the nourishment than during the storms; the TSS almost doubled. During the third sampling of the nourishment, the highest TSS concentrations were measured. The lowest concentration were measured during the first storm.

There were significant differences between the particles of organic origin too (Fig. 7). The relative content of organic particles (in %) was significantly higher at storms than at the nourishment. The content was twice as high during a storm than during any time of the nourishment. This did not apply to the total concentration of organic particles (in g per L). Nevertheless, the concentration during storms was still higher than

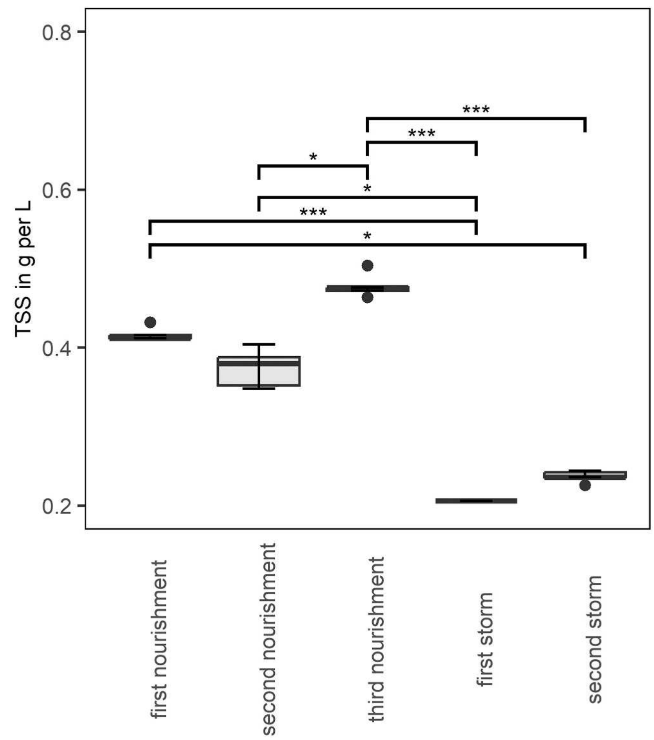

Fig. 6. Total suspended solids (TSS) concentration in g per L during the nourishments and storms. Values presented by Box plots are median (middle bar), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95 % of variability) and outliers (points). Significant differences are indicated by p values (p values < 0.001 are indicated by ***, p values < 0.01 by ** and p values < 0.05 by *).

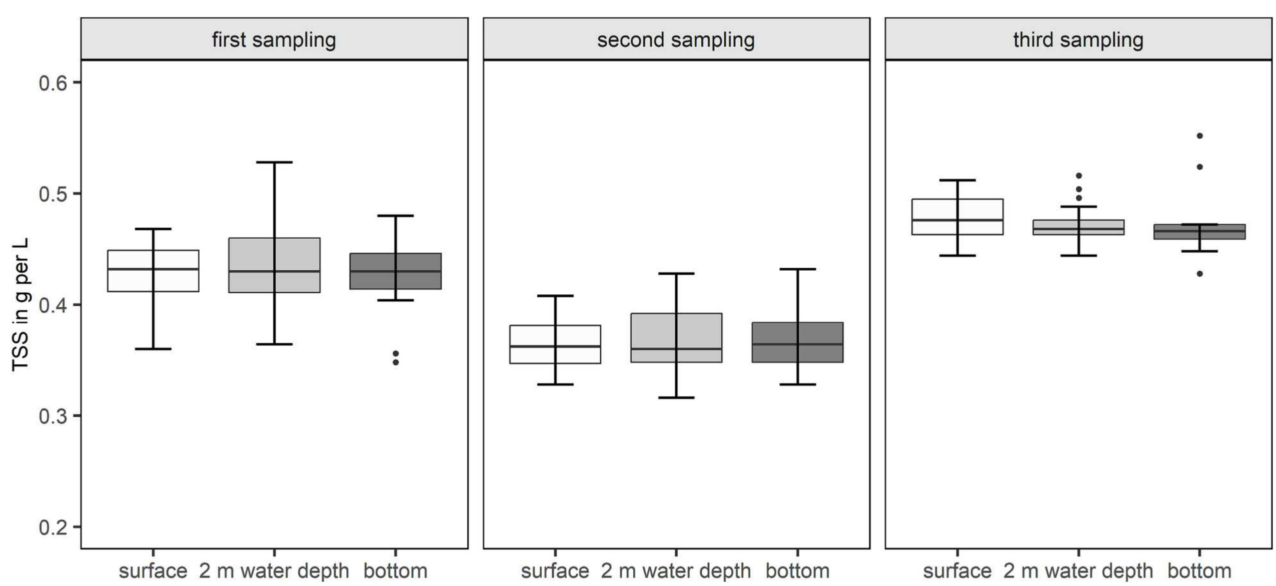

Fig. 5. Total suspended solids (TSS) concentrations in g per L during the three samplings of the sand nourishments. There were significant differences between the different nourishments but not between the different water depths. Values presented by Box plots are median (middle bar), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95 % of variability) and outliers (points).

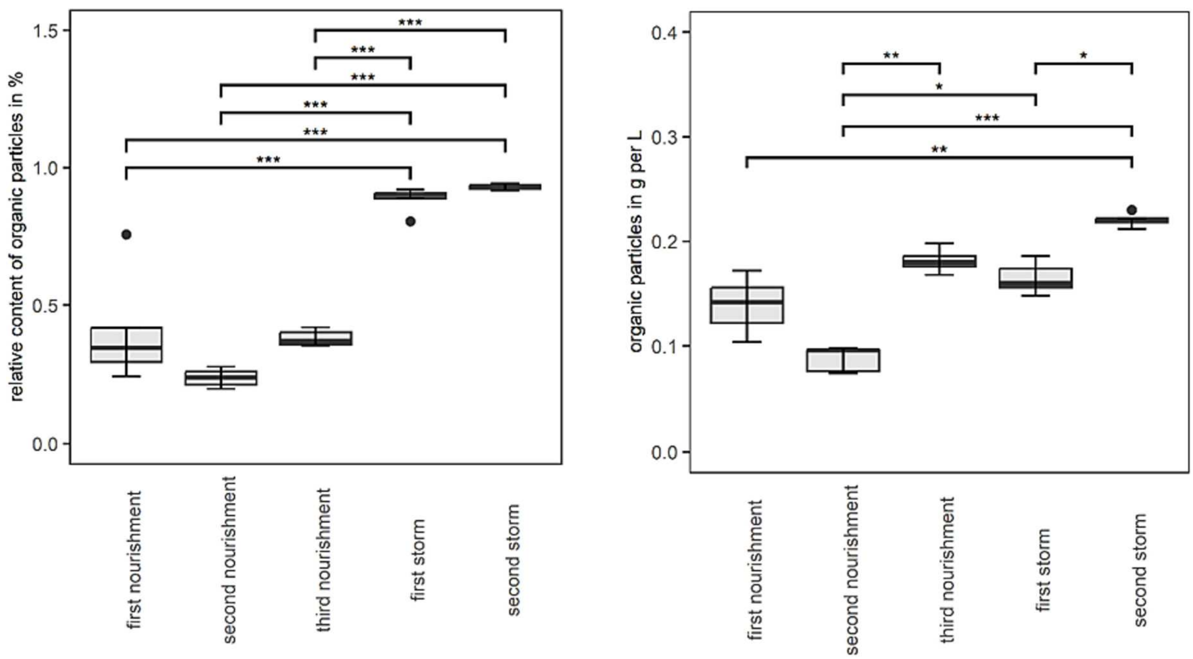

Fig. 7. Organic content of the total suspended solids (TSS) concentrations. On the left side is the relative content (in %) and on the right side the total content of organic particles (in g per L). Values presented by Box plots are median (middle bar), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95 % of variability) and outliers (points). Significant differences are indicated by *p* values (p values < 0.001 are indicated by ***, p values < 0.01 by ** and p values < 0.05 by *).

during the nourishments. Overall, the weight of particles of organic origin was very low, ranging between 0.08 and 0.23 g per L.

There were significant differences between the samplings concerning the nitrate concentration (Fig. 8). At the nourishment site, the concentration was increasing with every sampling. At the last sampling, the nitrate concentration was similar to the concentration measured during the storms. The concentrations during the different storm events did not differ significantly. There were only little significant differences

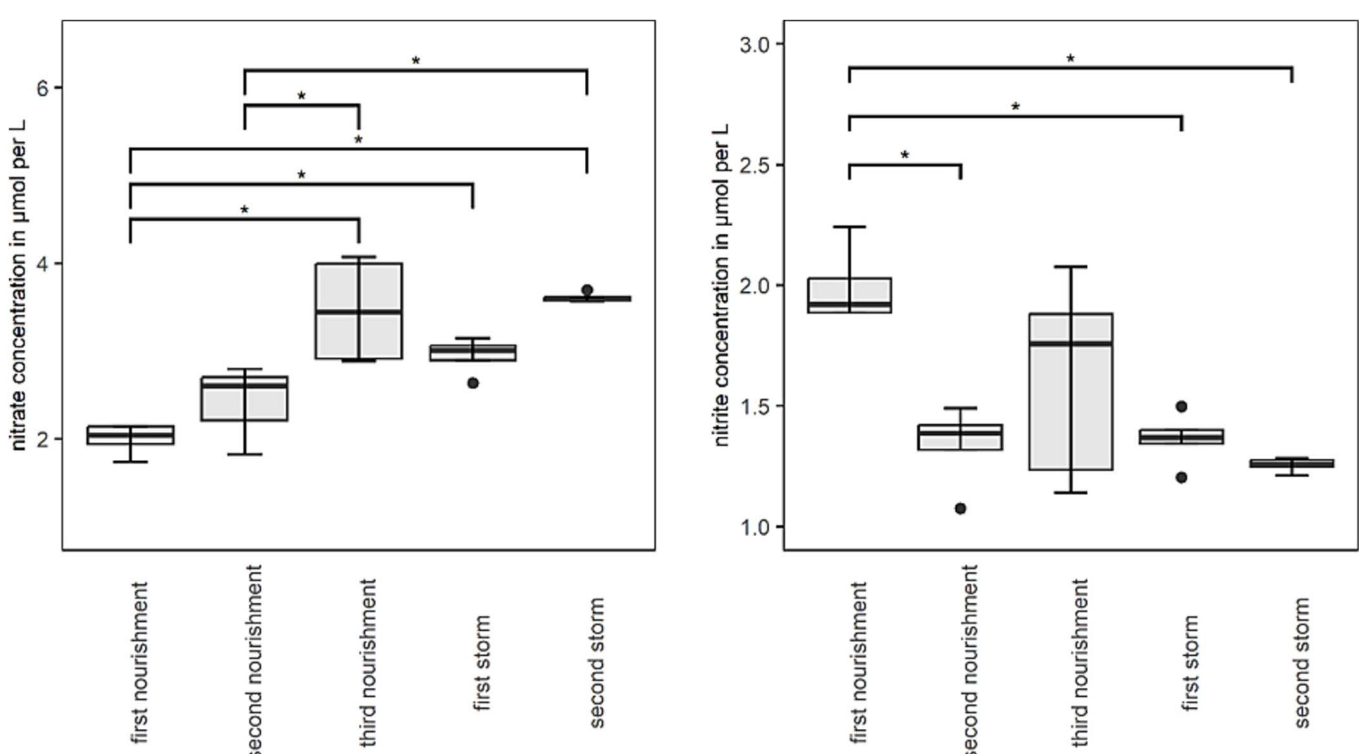

Fig. 8. Nitrate and nitrite concentrations in µmol per L in the water samples during the nourishments and the storms. Values presented by Box plots are median (middle bar), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95 % of variability) and outliers (points). Significant differences are indicated by *p* values (p values < 0.001 are indicated by ***, p values < 0.01 by ** and p values < 0.05 by *).

at the nitrite concentrations. Overall, the concentration varied a lot.

There were many significant differences concerning the phosphate concentrations at the different samplings (Fig. 9). The concentrations at the storm were significantly lower than at the nourishment, but the concentrations at the nourishment varied a lot. A similar picture is visible at the ammonia concentrations. In general, the ammonia concentrations at the nourishments are higher than during the storms. There are significant differences between the nourishments and the second storm, but due to variations in the concentration, there is no clear trend.

4. Discussion

There have been multiple reports and studies about the increased turbidity during sand nourishments all over the world (Nordstrom et al., 2004; Manning et al., 2014; Roegner et al., 2021; Roman-Sierra et al., 2011). Nevertheless, there is a lack of comparable data especially in the Baltic Sea region and the contextual connection to storm events – which can also cause turbidity in coastal zones. Therefore, we conducted the study to close this gap in knowledge and compare essential hydrological values of these two events.

One clear result of the pre-experiment is that the total suspended solids (TSS) concentrations are homogenous in the water column during the sand nourishment at Ahrenshoop. There was no increase of TSS concentration at the sea bottom which would indicate an accumulation of sediment particles near the bottom. However, differences in TSS concentrations during different phases of a nourishment are possible. Nevertheless, it is not necessary to distinguish between the different water depths if the samples are taken at the same time. A sand nourishment in Italy achieved a similar result (Capello et al., 2014). The sediment plume created by the nourishment had a homogenous distribution in the water column. But analysis also showed a small increase in TSS near the bottom. A possible reason why this is not visible in Ahrenshoop in the Baltic Sea is the mean water depth at the sampling site. While the mean water depth in Capello et al. (2014) is around 10–50 m, the mean water depth in Ahrenshoop was around 4 m. Due to this shallow area, the water column is probably more homogenous than at deeper sites.

Capello et al. (2014) reported TSS varying between 1.8 and 4.5 mg per L. The TSS concentration at the nourishment in Ahrenshoop was 100 times higher than at the nourishment in Italy. This is not only due to the nourishment activity, also the base TSS concentration without any additional activities was already 50 times higher than in Italy. This suggests that the mean turbidity in the Baltic Sea can be higher than in the Mediterranean Sea. Since this experiment did not include more samplings during other seasons of the year, this conjecture cannot be fully confirmed. Water samplings for turbidity analysis over several seasons could answer that question. The dependency of turbidity on the water body is also visible if you compare both data to a study conducted in New Jersey (Wilber et al., 2006). They reported TSS ranging from 31 to 176 mg per L. It is therefore necessary to compare not just the TSS concentrations during different nourishments but also to identify the basal turbidity at the habitats without any additional activity. Only with this knowledge can the comparison with the storm results be meaningfully carried out. These prerequisites are met here in this study.

While comparing the TSS of the nourishment with the TSS during storms, an elevation of the suspended solids is clearly visible. The TSS concentration is almost twice as high during the nourishment. Therefore, a sand nourishment increases the suspended sediments in the water column more than a storm event. But that does not mean, that storm events do not have an influence on the turbidity in coastal zones. This hypothesis is also supported by the research conducted by You (2005) who strongly encouraged scientists to integrate the influence of wind waves, wind-induced currents and ocean waves. The sedimentation during nourishments showed an additional increase if measured directly after a storm (Jordan et al., 2010). And hurricanes can have an even stronger effect as Wilber et al. (2006) reported. However, this effects seems to be limited to the swash zone, because no significantly elevated turbidity was measured at other shore zones. Nevertheless, the turbidity in the swash zone was ranging reportedly between 98 and 120 mg per L and they even had the highest turbidity during hurricane events exceeding the turbidity during sand nourishments. But they also identified that these highest TSS concentrations were measured at beaches that were nourished in the last year (Wilber et al., 2006). This suggests that the influence of storms on turbidity may have a greater effect in

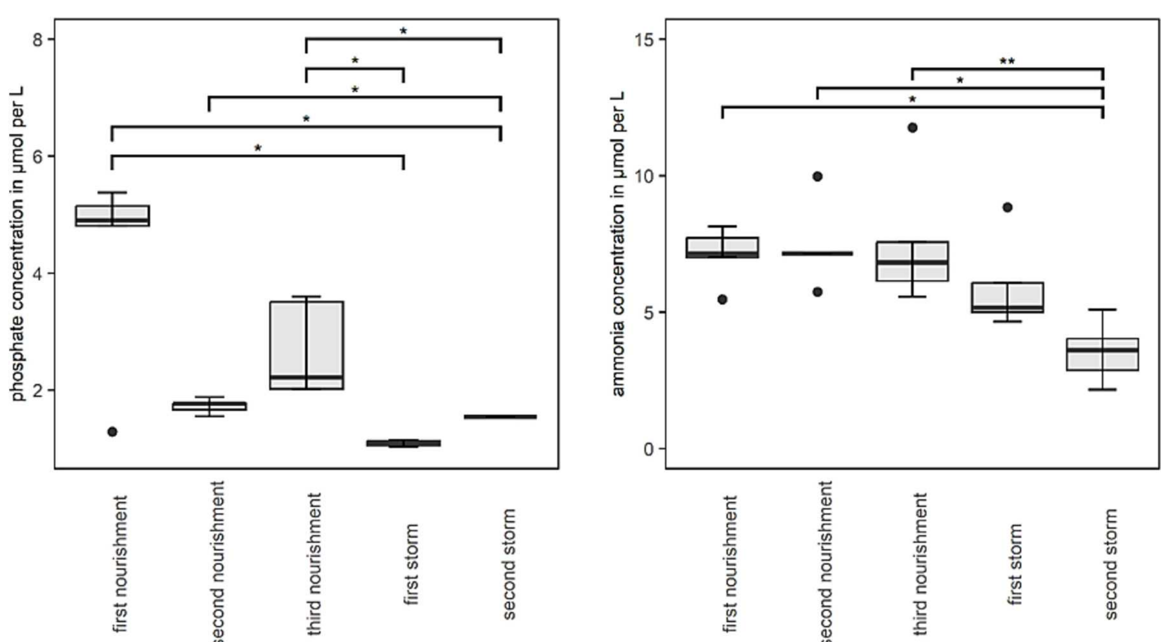

Fig. 9. Phosphate and ammonia concentrations in µmol per L in the water samples during the nourishments and the storms. Values presented by Box plots are median (middle bar), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95 % of variability) and outliers (points). Significant differences are indicated by p values (p values < 0.001 are indicated by ***, p values < 0.01 by ** and p values < 0.05 by *).

shallower zones of the coast (e.g. swash and surf zone) than was demonstrated in the present study. Further studies of the turbidity in different zones of the shore could answer this question. Jordan et al. (2010) also identified the wind direction as an important key factor to the turbidity. However, they suggested storm events only cause short term differences in the ecosystem. Wind direction and wind speed during the samplings were characteristic for winter conditions in the Baltic Sea which are dominated by strong winds from South and West. In rare cases, higher wind speeds were recorded (Leppäranta and Myrberg, 2009).

The TSS in the water column do not only consist of inorganic particles but also the organic fraction. The absolute content of those organic particles were very similar at both nourishment and storm events but the relative content was significantly different. At the nourishments, mostly inorganic particles were measured. This could be due to the nourishment process where the dredged sediment is washed out at the dredging site creating another turbidity plume (Capello et al., 2014). This plume consists of significantly finer sediment fractions than at the nourishment site indicating that most of the fine fraction is left at the dredging site (Qui and Sarkar, 2006). If this plume includes most of the organic fraction, the content of organic particles in reduced at the nourishment. This assumption can be confirmed by the fact that the organic content in the sediment sampled at the beach at the nourishment site also showed a very low organic content with around 0.26 % of wet weight. The mean grain size of 0.33 mm can be classified as middle sized sand and the sand is very well sorted (Sindowski, 1938) meaning that most of the sediment belongs to this grain size. During the storms in Graal-Mueritz, there was no sand nourishment, the suspended sediment did not have a reduced organic content. Therefore, the relative organic content in the TSS is higher.

Besides the turbidity, we analysed other hydrological values for the comparison of high turbidity events. This included the nutrient concentration of the water. Most of the nutrient concentration during the sand nourishment in Ahrenshoop and the storms in Graal-Mueritz varied greatly but there was no trend visible which event causes higher concentrations. In terms of nitrate concentrations, there was an increase during the whole nourishment event. This leads to the assumption that every nourishment action imported more nitrate into the system which accumulated there. The nitrate concentration after 3 months of nourishing was similar than the concentration during a storm event. The nitrite, phosphate and ammonia concentrations during the nourishments were at least as high as during storm events. These increased nutrient concentration can be the result of dredging sediment from deeper sediment layers. Most nutrients accumulated in the deeper layers and if these are dredged from the sea bottom, the nutrients are taken along. This could also explain the high variation in nutrient concentrations.

Since this study was the first of its kind comparing the effects of nourishments and storms on the turbidity in the Baltic Sea, results should be not viewed lightly. While the samplings during sand nourishments can be performed under normal conditions, this is not the case during storms. As the protection of human life is the top priority here, the samplings were performed under stressful conditions. This also prevented sampling from multiple water depths. Therefore, it is possible that TSS concentration during storms can vary between surface samples and sea bottom samples, the latter even exceeding TSS concentrations measured before. Lack of long-term measurements of turbidity in the Baltic Sea additionally complicates the classification of the measured values and only allows a comparison of the absolute figures and under these specific conditions. Other external factors, such as different kinds of sand nourishments and weather conditions can influence the ecological effects too. Nevertheless, this study may provide an idea of how turbidity differs between these two events and how large the local effects of sand nourishments may be in the Baltic Sea.

5. Conclusion

The sand nourishments in Ahrenshoop distributed mostly inorganic particles and less organic particles in the water column causing increased TSS concentrations. They also increased the nutrient concentrations to at least the same amount that can be measured during storm event on an adjacent shore. The TSS concentrations during the nourishments exceeded the ones during the storms. Therefore, the results of this study suggest that the influence of sand nourishments on shallow water coastal ecosystems can be higher than the influence of storm events on sandy beaches at the Baltic Sea. Additional studies to determine the temporal effect of nourishments, among others, are needed.

CRediT authorship contribution statement

Daniela Glueck: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing — original draft, Writing — review & editing, Visualization, Supervision.

The author confirms sole responsibility for the study.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Data availability

Data will be made available on request.

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Publication II: Ecological Impacts of Coastal Protection on the Vegetation of Sandy Coasts at the German Baltic Sea Coast

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Article

Ecological Impacts of Coastal Protection on the Vegetation of Sandy Coasts at the German Baltic Sea Coast

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Abstract: Sand nourishments and groynes as coastal protection measures (CPM) address similar challenges on sandy coasts but take different approaches: while groynes are intended to reduce alongshore sediment transport and erosion, nourishments add new sediment to the system to compensate for erosion. The aim of this study is to compare the ecological effects of such measures on the vegetation. To this end, nutrient analysis and botanical mappings were carried out on a site with installed groynes, a site where sand nourishments are regularly carried out, and a control site without any CPM. In addition to an increase in nutrient availability after the sand nourishment, significant changes in plant species diversity and composition were also measured. The number of higher plants, mosses, and lichen species was lower at the nourishment site. The opposite impacts were observed at the groyne site: an increase in sediment cover by higher plants and mosses and a distinct increase in lichen species. The results suggest that groynes lead to a stabilization of the coastal system and enable dense vegetation growth. In contrast, sand nourishments lead to nutrient input and unstable habitat conditions, attracting certain plant communities but preventing the establishment of ground-covering vegetation.

Keywords: sand nourishment; nutrient concentration; biodiversity; dune vegetation

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1. Introduction

Coastal dunes are exposed to numerous ecological challenges, including nutrient and moisture deficiency, sediment transport, and salt spray [1]. These challenges create spatial dynamics within the dune: the influences of wind, sand movement, and salt stress tend to decrease with increasing distance from the sea [2]. This gradient leads to an ecological differentiation and manifests itself in a zonation pattern characterized by different vegetation types (Figure 1). Nutrient-rich, moist beachwrack piles near the waterline provide a specialized habitat for nitrophytes and create wind shelter for sand accretion. This process promotes the establishment of pioneer vegetation that marks the formation of primary dunes. Within these primary dunes, species such as *Leymus arenarius* (L.) HOCHST. and *Elytrigia junceiformis* (Á. Löve & D. Löve) HAND & BUTTLER, as well as summer annuals including *Atriplex littoralis* (L.), *Cakile maritima* SCOP., and *Salsola kali* (L.), find a niche. The stabilization of the sediment and the further accumulation of sand are facilitated by the rhizomes of these plants [3–5]. Wind drift transports sand towards the land and leads to the formation of secondary dunes, the foredunes. The sand is stabilized by the large rhizomes of *Ammophila arenaria* (L.) LINK and *Elytrigia junceiformis*. These plants can catch sand and even grow through up to 40 cm of sand if they are buried underneath [3,5]. The wind-exposed, secondary white dune is still influenced by the interplay of wind-driven sedimentation and erosion [5]. The sand is lime-rich and maintains a high pH, yet it lacks humus [2]. The wind-sheltered side of the dunes transitions into the grey dune, which is characterized by changing microclimates and soil conditions [5]. In this area, although still relatively dry and exposed to the wind, the soil is leached and humus accumulates, leading to a pH shift towards acidic conditions and an increase in soil fertility [2]. Sandy grasslands predominate here with species such as *Corynephorus canescens* (L.) P. BEAUV., *Carex arenaria* (L.), *Jasione montana* (L.), pioneer mosses, and lichens [3,5]. This zonation of coastal dunes is usually stable but dynamic changes and developments are possible over varying timescales. The transition from a primary dune to a white dune can occur within a few years, the shift to a grey dune can take up to 10–20 years, and further progression to a brown dune can span over 60–70 years [5]. While these dune ecosystems demonstrate resilience, interventions such as storm floods, land subsidence, and tread damage can trigger regression and alter the established zonation [5]. To a certain extent, these disturbances can maintain dune mobility and offer an ecological niche for rare pioneer species [6] but anthropogenic disturbances in particular often lead to a loss of biodiversity [7].

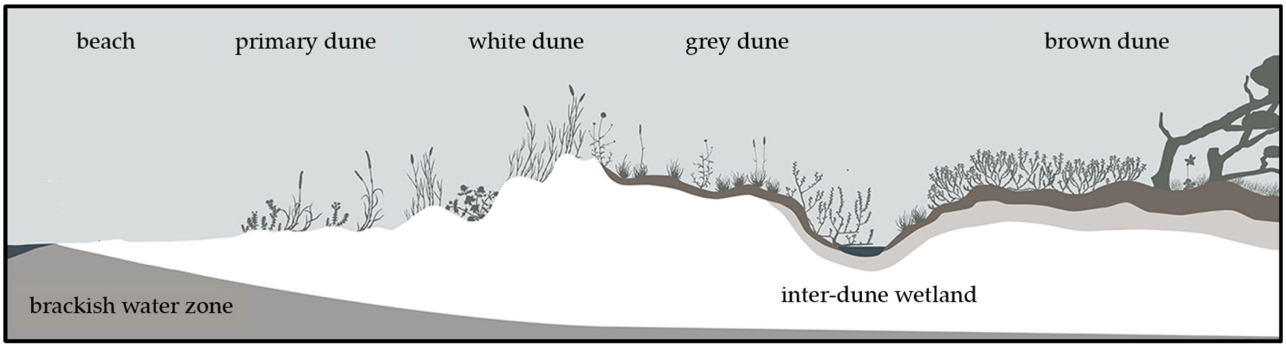

Figure 1. Cross-sectional overview of the stages of dune development and the most common terminology at the German Baltic Sea Coast. Adapted with permission from [8]. 2024, Sarah Mamerow.

Coastal protection measures (CPM), including sand nourishments and groynes, are essential strategies employed to safeguard vulnerable coastal regions. However, the coastal environments, including sandy beaches and dunes, already face significant threats such as coastal squeeze [9]. CPM can add more challenges to these coastal systems, e.g., by the introduction of foreshore structures, particularly hard structures to stabilize the coastline. They can affect sediment dynamics and hydrodynamic as well as depositional processes [10–12]. The consequences of the stabilization of formerly dynamic ecosystems are shrub invasion, increasing nutrient concentration, and a decrease in species variety [5]. Furthermore, ecosystem engineering processes by dune grasses are disturbed [13]. In contrast to those hard measures, soft measures were developed as more environmentally friendly techniques. Dunes, when appropriately managed, serve as a critical component of soft CPM too. However, it is important to recognize that the wear and erosion of these dunes are expected. Therefore, repeated nourishment becomes a necessary part of their maintenance. To extend the duration of sand nourishment projects, groynes or breakwaters are installed at the beach [14]. Although sand nourishments are considered as soft CPM, these actions can still affect the ecology of dunes starting with biota burial and habitat loss [10,12] leading to a reduction in the essential ecosystem functions [15]. Changes in plant diversity and coverage are believed to be the result of substantial anthropogenic action too [16]. Disturbances may lead to decreased plant coverage, but the implementation of CPM can also introduce nutrient inputs, fostering increased plant coverage by species adapted to nutrient-rich sediments [16], underlining the intricate ecological consequences of CPM in sandy beach and dune ecosystems.

The present study contains botanical mappings to study the following questions: (i) How is the vegetation composition changed due to the sand nourishment? (ii) Are there differences in the vegetation composition between nourished, groyne-protected, and unprotected coastal zones? (iii) How do species richness and biodiversity react to sand nourishments?

2. Materials and Methods

2.1. Study Site

The data were collected in Ahrenshoop and Graal Mueritz, two municipalities at the German Baltic Sea Coast (Figure 2, Ahrenshoop: 54°22′50.573″ N 12°25′16.506″ E and Graal-Mueritz: 54°15′34.412″ N 12°14′30.692″ E). Both municipalities are located on the Bodden compensation coast, which consists of different islands and spits. Hilltops of moraines are connected by narrow land bridges. These land bridges were formed by currents that eroded material from the island cores. The most important feature of this geographical region is the highly structured shape of the coast [17,18]. While the sediment supply for Graal Mueritz is ensured by sand transport from more western sections of the coast, the sediment supply for Ahrenshoop was originally ensured by cliff retreat. These cliffs are located in the 15 km coast section between the two municipalities and are actually protected by three breakwaters to prevent a retreat of the coast [18]. They are used as sediment traps to stabilize the shore but prevent the alongshore sediment transport from feeding the adjacent beaches. Through the missing sediment supply by cliff retreat, these high alongshore sand transport rates weaken the protective function of the dunes in Ahrenshoop and storm surges threaten the municipality. Therefore, sand nourishments are carried out every five to ten years [19]. The last nourishment in winter 2021/22 consisted of 600,000 cubic meters nourishing almost 4.5 km of coastline. The sand for the nourishment was extracted approximately 10 km from the coast from a sand deposit that had previously been inspected for suitability by the construction supervisors. The nourished zone in Ahrenshoop included parts of the beach, as well as the primary dune and the white dune (Figure 2). The coastal dynamic location in Ahrenshoop is representative of many places on the German Baltic Sea coast and was therefore chosen for the analyses and comparison. Furthermore, the timing of the coastal protection measure (CPM) was another reason why this site was chosen for the analysis: sand nourishments only happen at selected sites in Germany, and for the year 2021, only the coast of Ahrenshoop was nourished. Graal Mueritz has an almost identical geographic orientation compared to Ahrenshoop and is therefore suitable for comparison with the coast in Ahrenshoop. As CPM, wooden groynes are normally installed on the beach in some parts of the coasts. There is also a protected nature reserve near Graal Mueritz, in which coastal protection is not carried out. This offers the opportunity to sample an unprotected section of coastline.

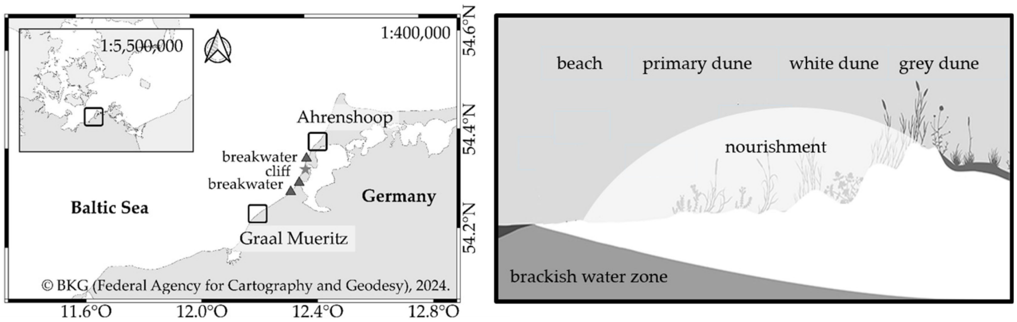

Figure 2. On the left side, sampling sites Ahrenshoop and Graal-Mueritz at the Baltic Sea, Germany. In Ahrenshoop, a nourishment took place in winter 2021/2022. In Graal Mueritz, wooden groynes are installed in some parts of the beach. Another part of the beach is without any coastal protection (=control site). On the right side is a cross-sectional overview of the placement of the nourished material at the coast in Ahrenshoop. Adapted with permission from [8]. 2024, Sarah Mamerow.

2.2. Performed Samplings

The sampling plan consisted of taking sediment samples in Ahrenshoop before and after the sand nourishment to determine nutrient concentrations in the sediment and botanical mappings to determine the biodiversity on the beach and dune (GPS coordinates of all sampling sites are shown in Table A1). The sediment cores were driven 20 cm deep into the sediment to determine sediment conditions within the germination and root growth depth of most seeds. For the results of the sediment characteristics (mean grain size, sorting, water, and organic and carbonate content), see [20]. For botanical mappings, all higher plants and mosses were determined. Lichen sampling was only performed once at the site. The sediment samples and botanical mappings were performed on the dates according to the following table (Table 1):

Table 1. Sampling plan for the performed sediment samplings and botanical mappings at the sites (Graal Mueritz and Ahrenshoop).

Date	Sediment Samplings:
7 April 2021	Graal Mueritz
21 July 2021 (before the nourishment)	Ahrenshoop
14 March 2022 (one month after the nourishment)	Ahrenshoop
19 May 2022 (3 months after the nourishment)	Ahrenshoop
11 August 2022 (6 months after the nourishment)	Ahrenshoop
25 May 2022 (more than one year after the nourishment)	Ahrenshoop
Date	**Botanical Mappings:**
22 July 2021	Graal Mueritz (incl. lichen)
16 August 2021 (before the nourishment)	Ahrenshoop (incl. lichen)
2 July 2021 (the year after the nourishment)	Ahrenshoop
11 July 2023 (two years after the nourishment)	Ahrenshoop

The concentrations of selected nutrients (nitrate, nitrite, phosphate, and ammonia) in each sediment sample were analyzed using the spectrophotometric method by Lambda 2, UV/VIS Spectrometer, and Perkin Elmer [21]. For this, 10 g of sediment was suspended in 50 mL of distilled water for one hour and then filtered through a glass fiber filter (pore size 0.45 µm, number of replicates n = 5).

Each botanical mapping consisted of 2 m wide belt transects (n = 5) from the beach to the end of the grey dune to determine species composition and soil coverage by higher plants. For this, long measuring tapes were placed vertically to the water line crossing all habitats from the beach to the coastal forest. On both sides of the measuring line, another line was placed in parallel at a distance of one meter. Within this 2 m wide area spanning from the waterline to the coastal forest, the plants were determined following Jäger et al. [22]. The percentage cover of each species was estimated using a modified and combined Braun–Blanquet abundance dominance scale (Table 2, [23]). Changes in species number and abundance were calculated with the Shannon Index H [24]. All lichens detected in the sampling area were collected by hand and stored in paper bags. The lichens were air-dried after collection and determined using a microscope with a maximum magnification of 400. The morphological identification of lichens followed Wirth et al. [25] including the nomenclature concept provided by Printzen et al. [26]. Some species of the genus *Cladonia* were analyzed using thin-layer chromatography according to Culberson and Amman [27] in solvent system A.

Table 2. Braun–Blanquet table [28] with determination of the degrees of vegetation coverage in percent and transformation in accordance with Ellenberg [23] coverage. With ind. = individual.

Frequency	Degree of Presence after Braun-Blanquet [26]	Transformed Cover Grade after Ellenberg [21]/%
Very seldom	r (=1 ind.)	0.1
	+ (=2–5 ind.)	0.2
Seldom	1 (<5% cover, but <50 ind.)	2.5
	2m (<5% cover, but >50 ind.)	5
Common	2a (=5–15% cover)	10
	2b (=16–25% cover)	20
Frequent	3 (=26–50% cover)	37.5
Mass	4 (=51–75% cover)	62.5
	5 (>75% cover)	87.5

For the statistical analysis, we used the R statistical software Version 4.0.3. The sediment samples were analyzed after checking for normality and variance homogeneity using an ANOVA or the Kruskal–Wallis test with the sampling site as the factor. The additional test was necessary since the requirements for the ANOVA were not met by all parameters. Post-hoc pairwise multiple comparisons were carried out using Dunn's Test against an alpha level of 0.05 to identify differences between the sampling times. For multidimensional scaling, the Bray–Curtis distance was used.

3. Results

3.1. Nutrient Concentration in the Sediment

There were significant changes in nutrient concentrations within the samples (Figure 3). The nitrate, nitrite, and ammonia concentrations increased after the nourishment at both the beach and the dune. The highest values were measured one month after nourishment. After that, the concentration started to decrease again. The phosphate concentration in the sediment increased after nourishment too. The highest values were measured after nourishment at both habitats. The concentration did not decrease between one and three months after nourishment. Six months after nourishment, the concentration had decreased again.

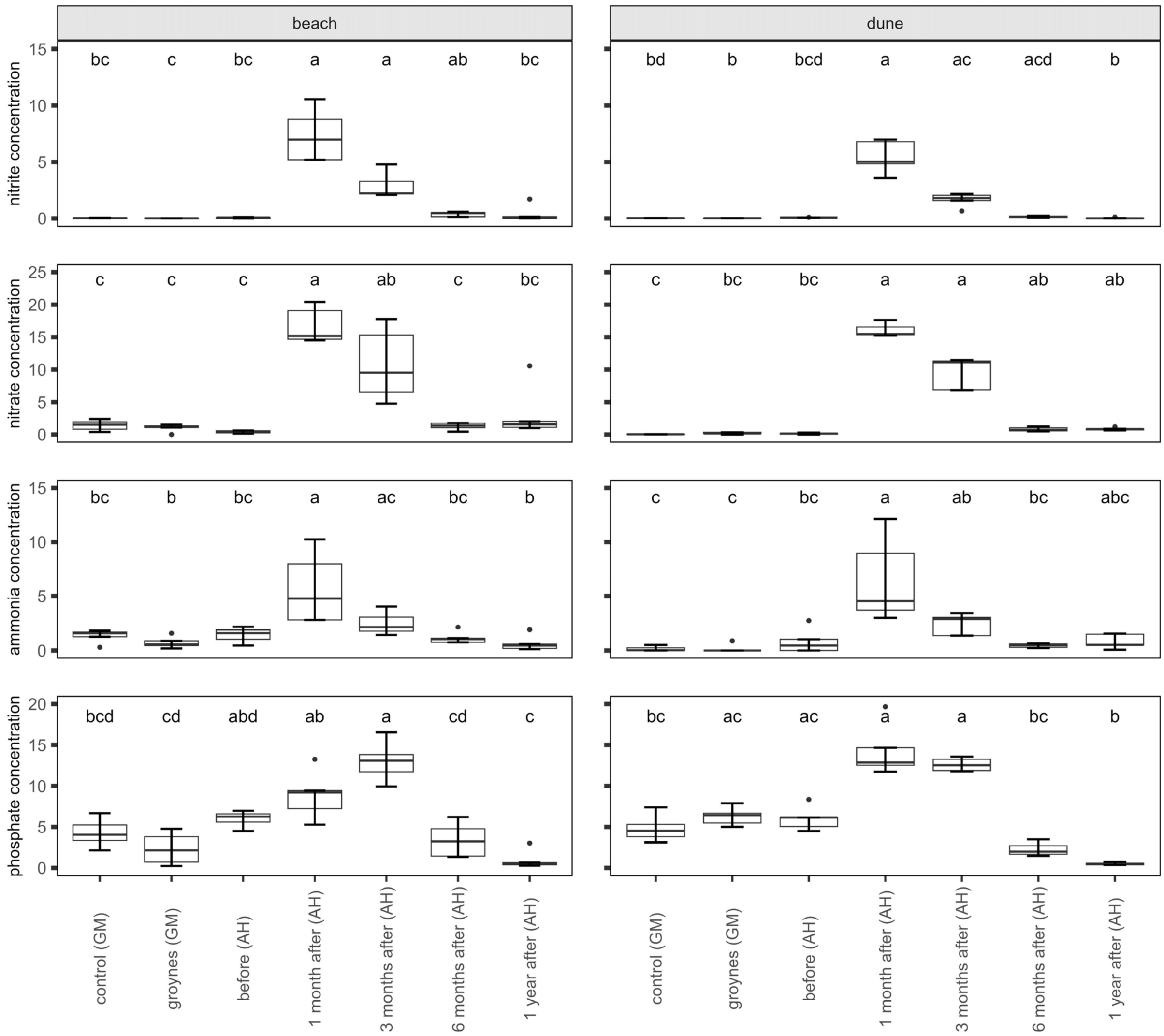

Figure 3. Nutrient concentrations (nitrate, nitrite, ammonia, and phosphate) of the sediment at the beach and dune in μmol per L. Shown are sediment samples from Ahrenshoop (AH) before, one month,

three months, six months, and one year after nourishment. For comparison, the species richness of two dunes in Graal Mueritz (GM, control, and groyne sites) is pictured. Values presented by Box plots are median (middle bar), and the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95% of variability) and outliers (points). Different letters indicate significant differences between sampling times (Dunn's Test, $p < 0.05$).

3.2. Botanical Mappings

Several botanical mappings were conducted to determine species richness as well as soil coverage. There were significant differences between the control sampling sites, groynes, and the sampling times at the nourishment site (Figure 4). There are two different trends visible: on the secondary dunes at the nourishment site, the species richness was generally lower than at the other two sites. There was a slight increase in species richness in the second year after nourishment. There were also significant differences between the Shannon Index H of the sampling sites. Just like the species richness, at the secondary dunes, the Shannon Index H was slightly lower at the nourishment site than at the control and groyne sites.

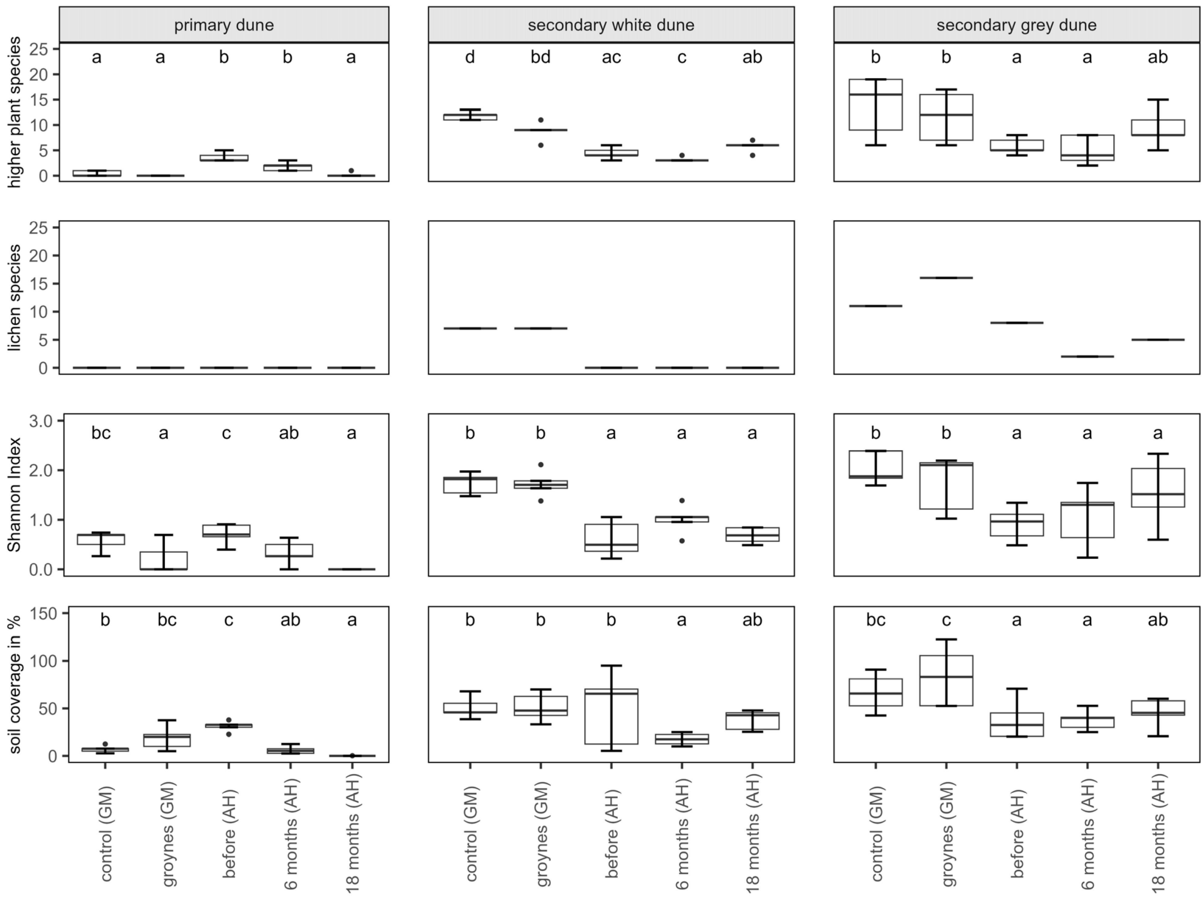

Figure 4. Number of higher plants and lichens, Shannon Index H, and soil coverage for each habitat (primary, secondary white, and secondary grey dune) in Ahrenshoop (AH) before, 6 months, and 18 months after the nourishment. For comparison, the species richness of two dunes in Graal-Mueritz (GM, control site, and groyne site) is pictured. Values presented by Box plots are medians (middle bar), and the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from 5 replicates. The Box plots also include whiskers (representing 5–95% of variability) and outliers (points). Different letters indicate significant differences between sampling times (Dunn's Test, $p < 0.05$).

These results of species number, soil coverage, and Shannon Index H are directly linked to the occurrence of the higher plant and lichen species in the mapped ecosystems. In the following table (Table 3), all detected species are listed, and the ecosystems where they were found are marked.

Table 3. Higher plant species and mosses (a) and lichen species (b) identified in the botanical mappings at Ahrenshoop and Graal Mueritz. Identified higher plant species are marked with grey shade. Light grey indicates a sediment coverage ≤10% and dark grey indicates a sediment coverage >10%. Marking X indicates the presence of a species without information about sediment coverage. Mapings were performed before sand nourishment in Ahrenshoop, as well as 6 months and 18 months after. In Graal Mueritz, the same mappings were performed on a site with groynes and on a site without any coastal protection (control). The mappings covered primary (P), secondary white (W), and secondary grey (G) dunes.

(a)	**Ahrenshoop**									**Graal Mueritz**					
	Before			**6 Months**			**18 Months**			**Groynes**			**Control**		
Higher Plant Species and Mosses:	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**
Acer pseudoplatanus (L.)									light						
Ammophila arenaria (L.) LINK	dark	dark	dark	light	light	dark	light	dark	dark	dark	dark	light	light	dark	light
Anthriscus sylvestris (L.) HOFFM.															light
Artemisia maritima L.									light						
Atriplex littoralis (L.)			light												
Brachythecium albicans (HEDW.) SCHIMP.												dark			dark
Bromus erectus HUDS.															light
Bromus hordeaceus L.															light
Cakile maritima SCOP.	light			light	light	light		light	light						
Carex arenaria (L.)		light	light			light		light	light		light	light		light	light
Cerastium holosteoides FR.		light	light			light			light		light	light		light	light
Ceratodon pupureus (HEDW.) BRID.									light						light
Corynephorus canescens (L.) P.BEAUV						light			light		light	light		light	light
Crambe maritima L.								light	light					light	light
Dicranum scoparium HEDW.									light			light			light
Elaeagnus sp. L.						light						light			
Elymus athericus (Link) KERGUÉLEN	light	light	light					light	light		light			light	
Eryngium maritimum L.		light	light						light					light	
Festuca pratensis HUDS.												light			light
Galium aparine L.												light			
Galium mollugo L.									light		light	light			light
Hieracium umbellatum L.		light	light		light	light		light	light		dark	light		light	light
Hippophae rhamnoides L.		light	light								light	light			light
Honckenya peploides (L.) EHRH.						light							light		
Hypochaeris radicata L.														light	light
Ilex aquifolium L.												light			
Jasione montana (L.)									light			light		light	light
Juncus tenuis WILLD.												light			light
Leymus arenarius (L.) HOCHST.	dark	light	light	light	light	light		light	light	light	light	light	light	light	light
Lathyrus japonicus subsp. maritimus (L.) P.W.BALL	light	light	light		light	light		light	light		light				
Melampyrum pratense L.												light			light
Nardus stricta L.											light				
Pinus sylvestris L.												light		light	light
Poa nemoralis L.												light			
Populus tremula L.									light			dark			dark
Pucinellia distans (JACQ.) PARL.												light			light
Quercus robur L.												light			light
Rosa canina L.			light												
Rosa rugosa THUNB.		light	light		light	light			light			light		light	
Rubus sp. L.						light			light			light			

Table 3. *Cont.*

(a)															
	Ahrenshoop									**Graal Mueritz**					
	Before			**6 Months**			**18 Months**			**Groynes**			**Control**		
Higher Plant Species and Mosses:	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**
Salix caprea L.												■			
Salix repens L.									■						■
Sedum acre L.						■									
Senecio vulgaris L.											■	■		■	■
Sonchus arvensis L.											■			■	
Spergularia marina (L.)													■		
Taraxacum sp. F.H.WIGG			■								■			■	■
Tripleurospermum maritimum (L.)						■									
Viola tricolor L.											■			■	■

(b)															
	Ahrenshoop									**Graal Mueritz**					
	Before			**6 Months**			**18 Months**			**Groynes**			**Control**		
Lichen and Lichenicolous Fungi:	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**	**P**	**W**	**G**
Amandinea punctata (Hoffm.) COPPINS & SCHEID.			l											A	
Cladonia chloropaea (Sommerf.) SPRENG.												s			
Cladonia fimbriata (L.) FR.												s			s
Cladonia furcata (Huds.) SCHRAD.															s
Cladonia gracilis (L.) WILLD.															s
Cladonia portentosa (Dufour) COEM.															s
Cladonia rei SCHAER.												s			s
Cladonia scabriuscula (Delise) NYL.															s
Cliostomum griffithii (Sm.) COPPINS											a	l			
* *Corticifraga fuckelii* (Rehm) D.HAWKS. & R.SANT.												P			
Evermia prunastri (L.) ACH.												s			
Hypogymnia physodes (L.) NYL.												l, s			
Lecania cyrtella (Ach.) TH.FR.			l						l		A			A, l	
Lecanora chlarotera NYL.			l												
Lecidella elaeochroma (Ach.) M.CHOISY											A, l	l		A	
Parmelia sulcata TAYLOR												l, m			
Peltigera canina (L.) WILLD.															s
Peltigera didactyla (With.) J.R.LAUNDON												s			
Peltigera rufescens (Weiss) HUMB.												s			s
* *Phoma peltigerae* (P.Karst) D.HAWKSW.												P			
Physcia adscendens H.OLIVIER			l						l		A, l	l			
Physcia tenella (Scop.) DC.			l, R			R			R		A, l	l		A, l	l
Polyozosia persimilis (Th.Fr.) S.Y.KONDR, LÕKÖS & FARKAS			l						l		A, l	l		A, l	l
Xanthoria parietina (L.) TH.FR.			l			l			l		A, l	l		A, l	l
* *Xanthoriicola physciae* (Kalchbr.) D.HAWKSW.			X											X	

* Lichenicolous fungus; A = *Ammophila arenaria*, l = litter, m = mosses, P = *Peltigera* spec., R = *Rosa rugosa*, s = sand, X = *Xanthoria parietina.*

These differences in species composition and vegetation coverage between the sampling sites can be used to illustrate similarities between ecosystems for both secondary white and grey dunes. In the following figure (Figure 5), neighboring points indicate a similar species composition and coverage. Increasing distance between points indicates increasing differences. For the secondary white dune, all points from the nourishment site are quite far away from the control and groyne sites while the data points representing the two sites are close to each other. The points representing the different sampling times at nourishment are close to each other as well. Similar, albeit not quite as pronounced, trends are also evident in the secondary grey dune: again, points representing the species composition at the control and groyne sites are distant from the ones at the nourishment site. In general, the points are closer to each other than at the white dune. The stress value for the calculation of the multidimensional scaling (MDS) was 0.1260, and the stress plot showed R^2 values of 0.984 (non-metric fit) and 0.901 (linear fit).

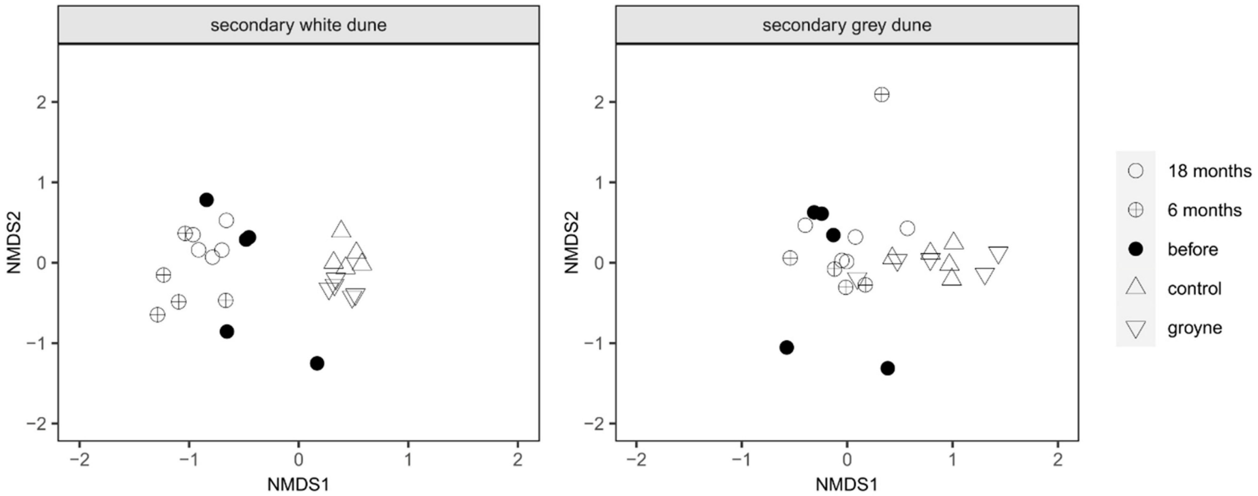

Figure 5. Multidimensional scaling (MDS) of the vegetation coverage on the white and grey secondary dunes at the three experimental sites and times: the nourishment site before, 6 months after, and 18 months after nourishment, with one site protected by groynes and another one without any coastal protection (control site).

4. Discussion

4.1. Nutrient Availability

The nutrient availability in sediments in dune ecosystems is very low compared to ecosystems with more fertile soils [29,30]. This low phosphate availability, but also the high buffering capacity, favors plant species that have adapted to these conditions [31]. Therefore, nutrient additions to these ecosystems can be seen as a major interference with the natural nutrient conditions. Seedlings growing in coastal ecosystems are able to bypass nutrient deficiency due to the availability of nutrients from the salt spray [32]. Another natural source of nutrient input is beachwrack, which washes up on the shore and then is decomposed by microbial communities and invertebrates leading to a release of organically bound nutrients [33]. During sand nourishment, nutrient-rich sediments taken from deeper sediment layers were exposed to the coast and nutrient concentrations increased [34]. Changes in the wave climate or meteorological climate were not responsible for the input of nutrients [34]. Therefore, an effect of nutrient addition on plant communities can be expected, e.g., a shift in species composition or increased plant biomass after the addition of nitrogen [35]. The germination and growth of seedlings can be significantly increased by fertilization too [36]. Nevertheless, this effect does not seem to occur everywhere in the same way or reacts only on larger time scales since there are reports that even after four years of increased nitrogen availability, no effects on dune plant species were measured [31]. Since the nutrient input after sand nourishment in Ahrenshoop was only temporary and decreased within six months, a direct effect could be limited.

4.2. Single Species Analysis

Most species that were found at the three sites are common dune species according to Bakker [3]. However, the changing abiotic habitat conditions are reflected in the abundance and distribution of plant species along transects at the coast. At the nourishment site, additional nutrient loads are a dominant factor influencing the performance of the plant species. An increased moisture content, which was detected during and after nourishment, could also have an influence on this [20].

Plant species profit from nourishment – One of those species is *Artemisia maritima*, which is known to profit from fertilization in salt marshes [35]. *Cakile maritima* is also known to grow best under high-nutrient and -moisture conditions, e.g., through beach wrack [33,37]. Both were found more frequently after nourishment, especially at the white dune. *Lathyrus japonicas* might have also profited as this species is not negatively affected by nutrient addition [38,39]. Similar results were noticed for *Sedum acre*, which has already shown increased growth after fertilization of the soil [40], *Honckenya peploides*, which has a broad spectrum for nutrient concentration in substrates [41], *Tripleurospermum maritimum*, which prefers nitrogen-rich substrates and shows increased growth after adding fertilizer [42], and *Salix repens*, known to grow better under increased nutrient concentrations [43,44]. Additionally, arbuscular mycorrhiza [43] enables species such as *Salix* sp. or *Rubus* sp. to maintain nutrient uptake at a steady level [45,46]. Symbiotic nitrogen-fixating bacteria within their stem and rhizome tissue [47] enable *Elymus athericus* to increase growth under high-nutrient conditions [35,37,48,49]. Other species that profit from the nourishment are highly competitive r-strategists known to respond with high rates of growth after disturbances. Some fast-growing shrub species, e.g., *Rosa rugosa*, show this behavior, resulting in large-scale vegetation composition changes. As this species is a strong competitor for space and nutrients [50], an increase in the spreading after nourishment is also possible. However, large-scale distribution of this species is prevented by complete coverage of the plants by sand in the nourished area, which the plants cannot survive. This explains why *Rosa rugosa* is rarely found at the white dune at the nourishment site but is common and increasingly found at the grey dune. More competitive species are *Hieracium umbellatum* and *Corynephorus canescens* [51,52]. Enduring plant species able to withstand unsuitable conditions were also recorded, e.g., *Jasione montana* [53], *Galium mollugo* [54], and *Crambe maritima* [38,55]. At the control and groyne sites, these species were found on multiple transects, showing that the species is also able to establish a certain coverage under better conditions.

Plant species inhibited by the nourishment—There are multiple reasons why plant species did not emerge after nourishment or decreased in the months after nourishment activities. One of them is the distribution of seeds of annual plants. This is the case for *Atriplex littoralis,* which could benefit from additional nutrients [35] but the annual plant is limited in its spreading of seeds. Less competitive species, e.g., *Cerastium holosteoides* [56,57], *Eryngium maritimum* [38,58], and *Rosa canina* [59], are also inhibited after nourishment. Another reason for the inhibition of species distribution is the elevated moisture in the sediment, which not every species can cope with. Although the genus *Taraxacum* includes many different species, with some of them even preferring periodically flooded areas [60], the species did not emerge after the measure.

Plant species not affected by the nourishment—Plant species that neither increased nor decreased were *Carex arenaria* and *Leymus arenarius*. Two years after nourishment, both species were still present on the white and grey dunes. A possible reason for the fast recovery is their root system and ability to acquire nutrients: *Carex arenaria* is a fast-growing species with roots up to four meters in length [61], and there have been reports of increased growth under high-nutrient conditions [54,62], as well as indirect evidence for nutrient transfer through clones [63]. For the dune species *Leymus arenarius,* arbuscular mycorrhiza has been reported [64]. Additionally, a wide-ranging root system enables plant species to acquire nutrients from adjacent areas [65], helping them to profit from increased nutrient loads, which can result in increased seedling establishment [66].

Plant and moss species detected only/mostly at the control and groyne site—There were several species occurring at both groyne and control sites but not or rarely at the nourishment site, indicating that this site is unsuitable. One of those species is *Brachythecium albicans*, a widely spread moss species that can be found on sandy substrates [67]. The moss species *Ceratodon purpureus* and *Dicranum scoparium* are also pioneer mosses appearing mostly in later successional dune stages [68]. These species did not appear on the freshly nourished dune but did at control and groyne sites. *Festuca* sp. and *Senecio vulgaris* dominate stabilized dunes under low-nutrient conditions [69–71]. Other species rely on already-developed soil to establish a population, which is only provided at the groyne and control sites, e.g., *Hypochaeris radicata* [72], or developed dune landscapes with depressions and increased soil moisture, e.g., *Juncus* sp. [73].

Melampyrum pratense and *Sonchus arvensis* are common plants growing on fixed dunes and contribute to sand-catching [3,74]. The species *Puccinellia distans* and *Poa nemoralis* are not common dune species but can survive if the ecosystem enables soil development [75,76]. This composition of different species in dense vegetation stands offers a habitat to other plants, such as *Nardus stricta* [77], *Ilex aquifolium* [78], and *Quercus robur* [79]. It is therefore not surprising to see those species appear on the stabilized dune. Low sediment dynamics can lead to increased coverage by lichens.

In contrast to species that rely on stable conditions, some plant species need a certain amount of disruptions and cannot establish themselves on completely fixed dunes, such as *Anthriscus sylvestris* [80], *Pinus sylvestris* [81], *Bromus* sp. [82], and *Thes tricolor* [83].

Lichen species–Lichen species, which are able to grow on *Ammophila arenaria* [68,84] on white dunes, were only present at the control and groyne sites. Species of the genera *Cladonia* and *Peltigera,* as well as the fruticose lichens *Evernia prunastri* and *Hypogymnia physodes* and the foliose lichen *Parmelia sulcata,* were only growing at these two sites, too. The species of the genera *Cladonia* and *Peltigera* occur on more or less acidic, rather nutrient-poor sand [25,68,84]. The other three lichen species usually grow epihytically [25,84], but they can also settle on rather nutrient-poor sand [68,84]. The settlement of all these species will only be possible if sand transport is reduced and the conditions are more stable. They mark the beginning of the development of grey dunes [2]. The contents of nutrient elements and organic matter in grey dunes are already higher than in white dunes [68,84]. The lichen species *Cladonia rangifera* has, in previous experiments, also reacted well to increased nutrients up to a certain level as a consequence of soil development [85], causing vegetation composition through soil coverage [86].

The number of lichen species was generally higher at the control site, and especially at the groyne site, than at the nourishment site. That means that the lower the sand dynamics, the greater the lichen diversity.

4.3. Vegetation Composition and Biodiversity

The biodiversity of coastal dune ecosystems is similar in most habitats. Embryo (primary) dunes, main (secondary white) dunes, and transition (secondary grey) dunes have similar species numbers [87]. To maintain this high coastal biodiversity, it is therefore important to conserve all habitats in the coastal system since all of them can contribute evenly to the biodiversity. Mobile dunes can have a higher plant biodiversity [6,88]. Indicators for a mobile dune are natural disturbances, e.g., regular wash-overs by waves or blow-outs by wind [88,89]. CPMs are usually opportunistic to these disturbances, either inhibiting them by stabilizing the dune or forcing oversized disturbances. Moreover, the replantation of certain species, e.g., *Ammophila arenaria*, used on a global scale for the reforestation of dunes [90], can lead to a reduction or disappearance of certain dune species [91].

Differences in species composition on the dunes are visible in this study in the results of the different CPMs: At the groyne site, the adverse effects of nourishment on plant diversity were only minimal, enabling lichen and moss species to persist. No additional sediment was flushed onto the dune, so no burial of existing vegetation happened, and the vegetation cover was able to develop. At the nourishment site, the additional sediment first led to the burial and destruction of the existing vegetation. In the second step, only young individuals of *Ammophila arenaria* were replanted. These changes caused a setback in the dune succession to a less stabilized dune more similar to embryo dunes or early white dunes. Increased eolian sediment transport can promote this even further and mainly reinforces the establishment of plants adapted to sediment movement. Moreover, although nourishment was limited to the beach and white dunes, the grey dune was also affected by these processes.

Active dune management, and primarily the removal of certain plant species, affects the vegetation composition as well. This influences shrub species the most as shrub invasion in dune systems causes the loss of grassland and leads to the enrichment of the soil and therefore is not a desired goal for dune development [60,92]. Both species of *Hippophae rhamnoides* and *Populus tremula* were affected by this removal at the nourishment site.

In general, the species detected at all sites are in the wide range of species numbers already published by other researchers for this region [7]. The number of species at the nourishment site is at the lower limit of this range. A low species richness is an indicator of missing habitat stability concerning abiotic and biotic conditions [93]. The lichen species numbers were also lower at the nourishment site. Lichen settlement starts only under stable habitat conditions, e.g., lower sediment dynamics, since they are not able to survive burial by sand. The soil coverage follows the same trend, although replantation of marram grass was performed. However, the necessary soil coverage of 30% to stabilize the sediment and inhibit eolian erosion was achieved [94]. In general, this study shows that the soil coverage by plants increases with increasing stabilization of the dune. While the coverage by marram grass decreases, the increase in heath and shrub species progresses even faster [90]. This supports the higher soil coverage measured at the groyne and control sites than at the nourishment site. The overall reduced species numbers are also shown by a decrease in plant diversity measured by Shannon Index H. While the plant diversity at the groyne and control sites is similar to earlier reports, the nourishment site again shows lower values than at other sites at the Baltic Sea, normally ranging between one and three [15]. On other coasts, this can be even higher. Reports from the Mediterranean Coast usually show diversity indices of around three to four with an increased species number [95]. Index H includes both the number of species and abundance to make an estimation of the diversity at the site, with a higher index indicating higher diversity.

Another factor that can influence the vegetation composition at the nourished dune is sediment characteristics changes after nourishment. Plant seedlings show both avoidance and tolerance strategies to withstand sediment stress, e.g., sediment moisture. However, especially on the dune, seedling establishment coincided with high moisture conditions [1]. During sand nourishment, additional moisture enters the sediment by flushing the sediment onto the coastal area. This was shown at the nourishment site in Ahrenshoop too, but like most other changes in sediment conditions, this was only temporary and was not measured after six months [20]. Therefore, the biggest influence on vegetation composition might not be the sediment characteristic changes, but rather the movement of sediment. This includes the burial of seedlings and seeds under nourished sediment that can significantly influence the emergence of seedlings [1]. In addition, it must also be noted that the overall sediment dynamics might have changed due to the regular nourishments [19] at the nourishment site for quite some time now. During normal dune succession, the replenishing sand for the dune originates from the beach and is moved in small quantities over a longer period of time [6]. In contrast, sand nourishments move large quantities of sediment over a small period of time leading to an overstabilized dune. These sand nourishments can increase eolian sand transport as well [96], and increased sediment movement can affect the plant species composition [97,98]. There are also demands for a change in nourishment practices, asking for either concentrated nourishment with larger amounts of sand instead of multiple repeated nourishment (e.g., sand motor in the Netherlands) to reduce the initial burial area [99] responsible for large biodiversity loss as a consequence of burial of all immobile and slow-moving organism [100] or mosaic nourishments to enhance the chances for natural recolonization [99].

5. Conclusions

Coastal protection measures (CPMs) are implemented with good reason and pursue a specific goal at their implementation site, e.g., erosion protection and flood reduction.

However, while doing this, they affect their surrounding ecosystems, which are already under pressure. Whereas the predominant practice was initially to stabilize the dune and beach and decrease erosion, there is now an increase in evidence supporting further effects. The species composition on nourished dunes suggests higher sediment mobility, while the more lichen- and moss-dominated vegetation at groyne and control sites indicate a stabilized habitat. Especially at the groyne site, the lichen species suggest a more mature dune system. Nutrient input by sand nourishment was only short term and the overall nutrient concentrations at the site were not increased by the regular repeated nourishments. These research findings can improve the current practice of coastal management: implemented CPMs should be closely monitored after installation, especially when they include repeated disturbances of the coastal system. Performed sand nourishments leading to reduced dune development and decreased soil coverage need to be compensated. This could include plant reforestation at the nourished dunes that include more diverse dune species increasing both sediment stability and biodiversity in these habitats. While the current practice is to restore only marram grass *Ammophila arenaria*, this could be extended to *Leymus arenarius* and *Corynephorus canescens* or other species. Other coastal protection measures should also be considered to counteract the cause of coastal retreat at this point. These could be, for example, additional, carefully placed breakwaters.

The decision for specific shore management is characterized by the available resources, littoral sediment transport, and also benefits such as recreational uses of the beach and dunes. The two fundamentally different coastal protection measures, repeated sand nourishment and groynes, were developed on the basis of these principles by coastal protection authorities ensuring either a dynamic or more stable coastal zone. The conflict of use in this heavily utilized environment will continue to have a significant impact on coastal protection in the future.

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Appendix A

Table A1. Coordinates of all sediment sampling stations in Ahrenshoop and Graal Mueritz. The botanical mappings were performed along transects, which span between the coordinates of each station.

Site	Station	Description	Longitude (Degrees East)	Latitude (Degrees North)
Ahrenshoop (sand nourishment)	1	Beach	12.412062	54.379118
	1	Dune	12.412390	54.378995
	2	Beach	12.423305	54.384627
	2	Dune	12.423598	54.384430
	3	Beach	12.430064	54.387775
	3	Dune	12.430459	54.387484
	4	Beach	12.436747	54.391684
	4	Dune	12.437031	54.391506
	5	Beach	12.443353	54.397647
	5	Dune	12.443826	54.397472

Table A1. *Cont.*

Site	Station	Description	Longitude (Degrees East)	Latitude (Degrees North)
Graal Mueritz (groynes)	1	Beach	12.272940	54.270792
	1	Dune	12.273260	54.270476
	2	Beach	12.272162	54.270477
	2	Dune	12.272439	54.270236
	3	Beach	12.271260	54.270152
	3	Dune	12.271525	54.269905
	4	Beach	12.270729	54.269949
	4	Dune	12.271000	54.269687
	5	Beach	12.269996	54.269632
	5	Dune	12.270210	54.269451
Graal Mueritz (control)	1	Beach	12.286490	54.275244
	1	Dune	12.286903	54.274995
	2	Beach	12.285852	54.274992
	2	Dune	12.286066	54.274792
	3	Beach	12.285117	54.274749
	3	Dune	12.285370	54.274512
	4	Beach	12.284139	54.274428
	4	Dune	12.284340	54.274221
	5	Beach	12.283473	54.274172
	5	Dune	12.283702	54.273967

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Publication III: Ecological consequences of breakwater and revetment structures on the Baltic Sea Coast in Germany

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Ecological consequences of breakwater and revetment structures on the Baltic Sea Coast in Germany

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ABSTRACT

Hard structures, such as breakwaters and revetments, while effective at mitigating coastal erosion, induce significant ecological alterations in terrestrial and aquatic environments. To study these effects, field investigations were performed along the Baltic Sea coast in Thiessow, Germany, highlighting breakwaters, a revetment and comparing them to an unprotected area. For this purpose, floristic mappings were carried out along transects on beach and dune. Algae scratch samples and sediment cores were taken, which were also used for nutrient analyses, each with a replicate number of n = 5. Sediment analysis revealed changes in grain size, sorting, water content, organic matter, and nutrient concentrations in areas influenced by breakwaters and revetments. These differences are less distinct on beach and dune. Finer sediments and increased organic content were observed in shallow waters near the breakwaters, while coarser sediments dominated near revetments. Vegetation surveys showed less dune plant species on the breakwater site and a pronounced shift towards ruderal plant species. Revetments eliminated terrestrial vegetation entirely due to their impermeable structure directly on the beach. The introduction of hard substrate in soft-bottom habitats in the shallow water favours the settlement of macroalgae, whereby there is only a weak zonation with regard to the distribution of species on the structures. Meanwhile, no seagrass meadows were recorded near the breakwater which could indicate supressing effects. These findings underscore the ecological consequences of hard coastal protection and emphasize the importance of integrating ecological considerations into coastal protection strategies to balance shoreline stabilization and preservation of natural habitats.

1. Introduction

Around 28 % of the global human population lives in the near-coastal-zone and the trend is rising (Reimann et al., 2023). As a results of this dynamic, the need for protection of these coasts is also growing. However, the importance of coastal protection has not only increased due to increased settlement pressure, but also against the backdrop of climate change and its effects. With accelerated sea level rise, storm floods and increased coastal erosion coastal protection becomes even more important (Airoldi et al., 2005). Coastal protection defence structures are widely spread all over the world and became a common part in many coastal landscapes (European Commission, 2004). The following management approaches are used (Sundar, 2022): adaptation of infrastructure, retreat from the coast and defence of shoreline. The latter category can be subdivided into hard measures (breakwaters, seawalls, etc.), soft measures (beach nourishments, vegetation on dunes, etc.) and combined "hybrid infrastructure(s)" (seawall combined with salt marsh) (Sundar, 2022). Most of the used coastal protection measures fall into the category hard measures, as they are the most conventional methods and show the fastest and representative results in stabilising the shoreline by letting waves break ashore and reducing the lateral sediment transport along the coastline (Airoldi et al., 2005; European Commission, 2004; Sundar, 2022). Hard measures include hard structures such as breakwaters, groins and dikes, using solid materials like concrete and soft structures like geo-synthetics (European Commission, 2004; Sundar, 2022). Breakwaters are detached from shore, but placed parallel to the coastline. They are either found submerged, low crested or emergent (European Commission, 2004; StAUN Rostock, 2009; Sundar, 2022).

As an expansive infrastructure, the efficiency of coastal protection measures with respect to protection and change in morphodynamics has been extensively assessed (Airoldi et al., 2005; Martin et al., 2005;

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Moschella et al., 2005; Sundar, 2022; Vaselli et al., 2008). However, such interventions in dynamic ecosystems and accordingly significant impacts on coastal ecosystems, shown by Van Duren (2011) can have transregional consequences. So far, no systematic recording of these consequences is known; this only takes place in the context of undesirable side effects, e.g. invasive species or commercial fishery, as species-focused studies (Martin et al., 2005; Vaselli et al., 2008). By introducing new solid structures into the ecosystem, possibly made out of foreign material, alien species can be attracted. This can lead to unforeseen additions to the biodiversity in the ecosystem, potentially altering the ecological landscape. The risk of alterations in the organism composition increases when placing hard structures on otherwise sandy shores (European Commission, 2004; Martin et al., 2005; Moschella et al., 2005).

Therefore the ongoing challenge is that the full range of impacts, especially the ecological effects of breakwaters, revetments and other introduced structures on the coastline remains poorly understood due to limited available data (Airoldi et al., 2005; European Commission, 2004). What's more, the already existing investigations usually take place either on water or on land, so that uncertainties remain in the assessment processes prior to coastal construction planning. Therefore, this study attempts to integrate both systems and provide a comprehensive overview. For this purpose, the following research question were asked: (i) How does the extend vary to which sediment characteristics change along coastal sections with breakwaters, revetments or not protected sections and (ii) how does the vegetation change due to the introduction of hard structures in the coastal zone in the form of breakwaters and revetments?

2. Material and methods

2.1. Sampling site

Investigations were done in Thiessow (54°16'21.4"N and 13°42'17.4"E, Fig. 1). Thiessow is a district of the municipality of Mönchgut, located in the south-east of the island Rügen, in the federal state Mecklenburg Western Pomerania. The sampled coastline faces the Greifswalder Bodden. The control transects were placed inside a small bay that formed at the tip of the Mönchgut peninsula, facing south. The decision to use this control location was primarily due to the limited choice of other undisturbed locations, as there are none left: the bay with the breakwaters is adjoined by a section of cliffs at the northern site that are not suitable for sampling, while the rest of the coastline is already covered with coastal protection measures. Transects containing the breakwaters and revetment were located on the coastline facing southwest. The characteristics of the coastline are influenced by human activity, featuring sandy beaches, a coastal protection forest, and tourist walkways. In 1990/1991 the revetment was installed as a coastal protection measure with a length of 538 m. In 1992 a system of five breakwaters with a total length of 400 m was installed at the coastline (StAUN Rostock, 2009).

2.2. Sampling terrestrial and aquatic vegetation

Floristic assessment was conducted by transect-mapping along the beach-system on 24.05.2023. Transects of 2 m width, starting at water level and reaching perpendicular to the shoreline until the end of the dune were mapped for plant species occurrence and dominance. Each transect was subdivided into a beach zone, white and grey dune representing the zonation pattern of coastal dunes. Primary dunes mark the establishment of a pioneer vegetation. Wind-driven sedimentation and erosion are one of the biggest influencing factors on the white dune. Increasing plant coverage and wind shelter leads to the formation of the grey dunes (Kollmann et al., 2019). On two sites (control and breakwater), five transects were surveyed each. At the revetment site, beach and dune were missing. Therefore, no transects were surveyed here. The flora was visually quantified and identified with Parolly and Rohwer (2016) and the use of the phone application 'Flora Incognita' (Technische Universität Ilmenau, 2018). The abundance of species was described according to the Braun Blanquet-Scale (Braun-Blanquet, 1964) which takes the number of individuals or ground cover per species into account.

For the macrophyte sampling, scratch samples (number of replicates n = 5) were taken from the breakwater (in front and behind) and the revetment on 19./20.04.2023. The macrophytes were visually examined qualitatively and characterized for their species and occurrence using a binocular and the identification key by Nielsen and Lundsteen (2019) the day after the sample collection. Sampling stations without any hard substrates were visually examined for sediment-attached macrophyte vegetation.

2.3. Sediment cores

Sediment cores were taken at three or four different distances from shore (20 m from shore, 77 m / 80 m / 83 m from shore and 100 m from shore at depths of 0.20 m, 2.50 m and 4.00 m) and also on the beach and dunes (Fig. 2). Number of replicates was n = 5 if not mentioned otherwise. Behind the revetment the terrestrial part of the transects was modified to a pedestrian street, terrestrial mapping and the effect of the revetment could not be assessed. The aquatic sediment cores were taken

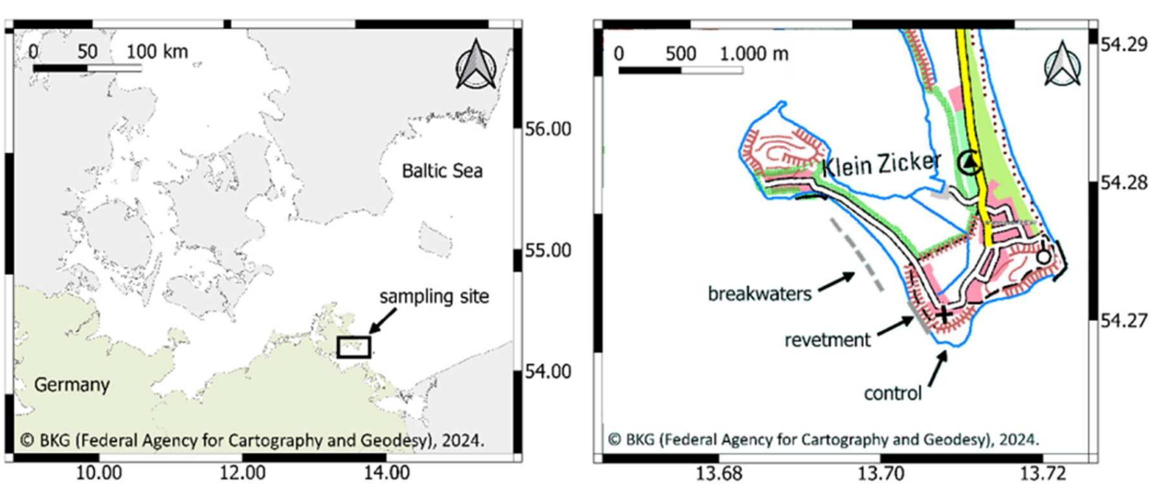

Fig. 1. Map of investigated sampling site. Left: Baltic Sea and Germany, Denmark and Sweden are visible. Right: Location of the sampling site at the Isle of Rügen in Thiessow. Sampling positions at breakwaters, revetment and control are shown.

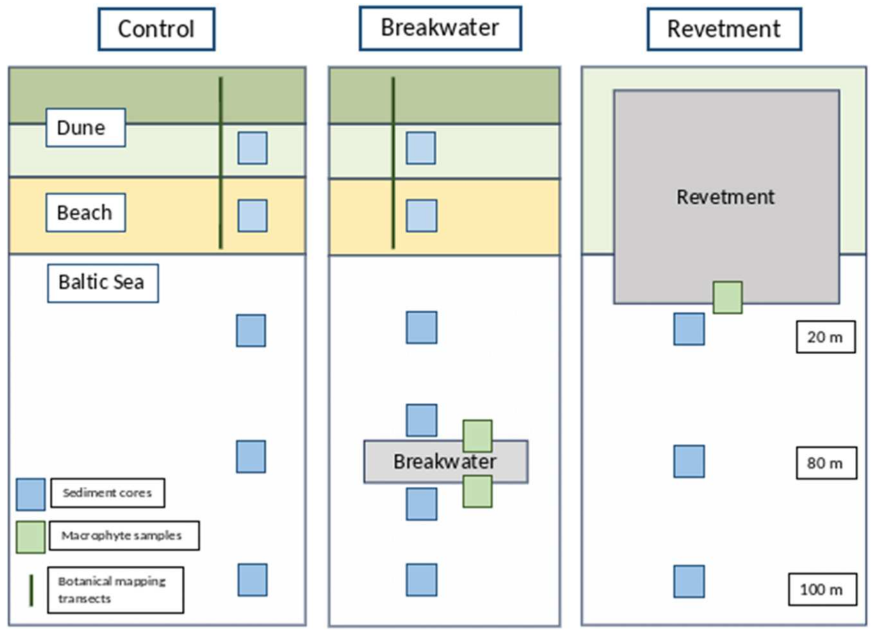

Fig. 2. Conceptual sketch of the sampling positions at control, breakwater and revetment. The transects are partitioned into dune (grey dune = dark green, white dune = light green), beach (sandy beach) and Baltic Sea (20 m from shore = 0.20 m water depth, 77 m / 80 m / 83 m from shore = 2.5 m water depth, 100 m from shore = 4.0 m water depth).

on 19./20.04.2023. The terrestrial sediment cores were taken on the 24.05.2023 on a dry day with no rain or storms the days before. The sediment cores used for the analyses had a diameter of 3.6 cm and were manually inserted to a depth of 20 cm into the sediment. They were then transported vertically to the laboratory. The water content and organic content was determined via Schlungbaum (1979) with a 5 mL mixed subsample of the sediment core. The grain size distribution was determined after Schlungbaum (1979). The D_{50} (mean diameter of the grain) and the sorting grade according to Sindowski (1938) were determined. The mean grain size was classified according to the Udden-Wentworth grain size classification (Wentworth, 1922).

2.4. Nutrient measurement

The nutrient concentrations (nitrate, nitrite, phosphate and ammonia) in each sediment sample were analysed using the spectrophotometric method by Lambda 2, UV/VIS Spectrometer, and Perkin Elmer (Grasshoff et al., 1999). 10 g sediment was suspended in 50 mL distilled water for one hour and then filtered through a glass fibre filter with a pore size of 0.45µm (number of replicates n = 5).

2.5. Data analysis

Statistical analyses were conducted with R (R Core Team, 2022). Data were analysed for normality and homogeneity by means of Shapiro-Wilk and Levene test. In case of normal and homogeneous distribution, data were analysed with an analysis of variance (ANOVA) and Tukey Honestly Significant Difference (HSD) post-hoc test. The vegetation composition was analysed with paired permutational multivariate analysis of variance (PERMANOVA). Non-normally distributed data were analysed with the Kruskal-Wallis test and Fisher Least Significant Difference (LSD) post-hoc test (de Mendiburu, 2021). Significance levels were set to a p-value < 0.05.

The vegetation composition was visualized via non-metric multidimensional scaling (NMDS) from the vegan package. This visualisation is particularly suitable to record changes in the species composition of communities by using ranks instead of distances. An analysis of similarity (ANOSIM) was used to determine whether there are statistically significant differences between the sites with a significance level $p < 0.05$.

3. Results

3.1. Sediment

Overall, the sediments from the aquatic sampling sites exhibited more pronounced differences compared to the terrestrial sediment samples (Table 1). The terrestrial samples only showed significant differences concerning the water content and the phosphate concentration: The water content on the beach at the breakwater site was higher than at the control site, while the dune at the control site had higher water content than the breakwater site. The phosphate concentration was higher at both beach and dune at the breakwater site in comparison with the control site. The aquatic sediment samples showed more significant differences. At the breakwater site, overall smaller grain sizes were recorded and in front of the structure a very well sorted sediment was present. Higher water content in the shallower water with higher organic content and ammonia concentration in comparison with the unprotected site, were recorded as well. In contrast, the revetment showed coarser grain sizes right in front of the structure in comparison with both other sites and an overall poorly sorted sediment. Higher organic content with increased nutrient concentrations were recorded near the structure when comparing with the unprotected site as well.

3.2. Terrestrial vegetation

The highest coverage showed the grey dune at the control site and the white dune at the breakwater site. The control site had higher coverage on the grey dune than the breakwater site. The breakwater site had a higher coverage on the beach and white dune. In total, 19 higher plant species were detected. 16 of these species were found on the breakwater transects and 12 on the control transects (Table 2).

These differences in species composition and vegetation coverage between the sampling sites can be used to illustrate similarities between ecosystems for the beach and dune systems. As the revetment covers both areas completely and prevents any vegetation from establishing, a

Table 1
Comparison of terrestrial and aquatic sediment data (mean ± SD) at the dune, beach, 20 m, 77 m, 80 m, 83 m and 100 m from shore. Listed are grain size (mm), sorting degree, water (% of wet weight) and organic content (% of dry weight), nitrate (μmol L^{-1}), nitrite (μmol L^{-1}), ammonia (μmol L^{-1}) and phosphate (μmol L^{-1}) concentration. Sample size was n = 5, except for 100 m position at the breakwater site, where only three sediment samples were analysed. Different letters indicate significant differences (HSD or Fisher LSD post-hoc test, p < 0.05) between sites which was tested at each position.

Terrestrial sediment data

position	**site**	**grain size**	**sorting degree**	**water content**	**organic content**	**nitrate**	**nitrite**	**ammonia**	**phosphate**
dune	control	0.37 ± 0.02 a	1.69 ± 0.09 a	1.61 ± 0.31 a	0.26 ± 0.09 a	2.41 ± 2.01 a	0.19 ± 0.08 a	n. d.	1.5 ± 1.07 a
	breakwater	0.37 ± 0.01 a	1.68 ± 0.09 a	0.28 ± 0.27 b	0.34 ± 0.10 a	0.81 ± 0.34 a	0.12 ± 0.03 a	n. d.	2.33 ± 1.00 a
beach	control	0.43 ± 0.05 a	1.27 ± 0.32 a	0.15 ± 0.17 b	0.40 ± 0.21 a	7.46 ± 3.93 a	0.23 ± 0.08 a	0.30 ± 0.26 a	1.29 ± 0.21 b
	breakwater	0.45 ± 0.04 a	1.17 ± 0.26 a	2.29 ± 1.11 a	0.23 ± 0.12 a	10.9 ± 5.22 a	0.42 ± 0.17 a	0.82 ± 0.64 a	2.1 ± 0.66 a

Aquatic sediment data

position	**site**	**grain size**	**sorting degree**	**water content**	**organic content**	**nitrate**	**nitrite**	**ammonia**	**phosphate**
20 m	control	0.53 ± 0.05 a	0.44 ± 0.24 b	15.9 ± 1.48 a	0.48 ± 0.16 a	0.56 ± 0.30 a	0.36 ± 0.12 a	4.55 ± 5.37 a	1.00 ± 0.16 a
	breakwater	0.28 ± 0.03c	1.37 ± 0.40 a	18.4 ± 0.68 b	0.34 ± 0.01 b	0.67 ± 0.23 a	0.28 ± 0.07 a	2.58 ± 1.54 a	1.01 ± 1.06 a
	revetment	0.83 ± 0.01 b	0.05 ± 0.04c	17.0 ± 0.64 ab	0.48 ± 0.08 a	0.81 ± 0.17 a	0.40 ± 0.05 a	4.46 ± 2.45 a	1.43 ± 0.54 a
77 m	breakwater	0.18 ± 0.02c	1.16 ± 0.13 a	19.2 ± 1.75 a	0.63 ± 0.18 a	0.54 ± 0.18 b	0.53 ± 0.07 ab	4.80 ± 6.12 a	0.93 ± 1.06 b
80 m	control	0.57 ± 0.15 a	−0.19 ± 0.20 d	14.4 ± 0.76 b	0.52 ± 0.11 ab	1.37 ± 0.59 a	0.79 ± 0.20 a	0.86 ± 0.69 a	2.02 ± 0.86 a
	revetment	0.43 ± 0.02 a	0.94 ± 0.11 b	16.3 ± 0.38c	0.34 ± 0.04 b	0.35 ± 0.06 b	0.34 ± 0.18 b	2.06 ± 2.50 a	1.55 ± 1.82 ab
83 m	breakwater	0.27 ± 0.02 b	0.53 ± 0.05c	18.7 ± 2.30 ac	0.60 ± 0.13 a	2.13 ± 0.50 a	0.96 ± 0.32 a	2.57 ± 2.32 a	1.06 ± 0.44 ab
100 m	control	0.85 ± 0.02 a	0.30 ± 0.19 b	16.1 ± 1.12 b	0.52 ± 0.09 b	1.83 ± 0.62 a	0.44 ± 0.22 b	0.41 ± 0.42 a	0.25 ± 0.03c
	breakwater (n = 3)	0.38 ± 0.02 b	1.07 ± 0.40 a	15.9 ± 0.57 b	0.46 ± 0.07 b	1.86 ± 0.97 a	0.88 ± 0.65 ab	2.99 ± 2.17 a	0.93 ± 0.40 b
	revetment	0.10 ± 0.03c	−0,15 ± 0.12 b	20.0 ± 1.10 a	1.27 ± 0.08 a	1.94 ± 1.11 a	1.66 ± 1.00 a	1.27 ± 1.45 a	2.74 ± 1.31 a

Table 2
Higher plant species identified in the botanical mappings at the sites control (C) and breakwater (B). Identified higher plant species are marked with grey shade. Light grey indicates a coverage up to 5 % and dark grey indicates a coverage higher than 5 %. The last row shows total coverage (mean ± SD) by plants in %. Sample size was n = 5. The mappings covered the beach, white and grey dune.

	beach		white dune		grey dune	
Higher plant species:	**C**	**B**	**C**	**B**	**C**	**B**
Ammophila arenaria (L.) Link	light grey	light grey	dark grey	dark grey	dark grey	dark grey
Arrhenatherum elatius (L.) J.Presl & C.Presl		light grey		dark grey		dark grey
Artemisia maritima L.	light grey			light grey		light grey
Cakile maritima Scop.	light grey		light grey			
Calystegia soldanella (L.) Roem. & Schult.				light grey		
Carex arenaria L.			light grey		light grey	
Cerastium holosteoides Fr.				light grey	light grey	light grey
Galium mollugo L.			light grey		light grey	
Galium verum L.				light grey		light grey
Geum urbanum L.		light grey		light grey		
Hieracium umbellatum L.			light grey	light grey	light grey	light grey
Honckenya peploides (L.) Ehrh.	light grey	dark grey	light grey	light grey		light grey
Lactuca tatarica (L.) C.A.Mey.				light grey		
Lathyrus japonicus subsp. *maritimus* (L.) P.W.Ball					light grey	light grey
Leymus arenarius (L.) Hochst.	light grey	light grey	light grey	light grey	light grey	light grey
Phragmites australis (Cav.) Trin. ex Steud.				light grey		light grey
Rumex crispus L.						light grey
Senecio sp. L.		light grey	light grey	light grey	light grey	light grey
Taraxacum sp. F.H.Wigg				light grey	light grey	light grey
coverage by plants / %	2.1 ± 2.6	13.2 ± 7.4	37.6 ± 26.9	55.0 ± 18.5	55.6 ± 12.0	31.9 ± 15.3

comparison with this site is not possible. Therefore, only the control and the breakwater site are compared. Significant differences in species composition between the control and the breakwater site at the beach (p = 0.008) and at the grey dune (p = 0.009) were measured. In the following figure, neighboring points indicate a similar species composition and coverage of higher plant species (Fig. 3). Increasing distance between points indicate increasing differences between the sites. For the beach, this visualization shows the most differences as there are no overlaps between the sampling sites. Similar distinct results show the white dunes, but there is already an overlap between the site

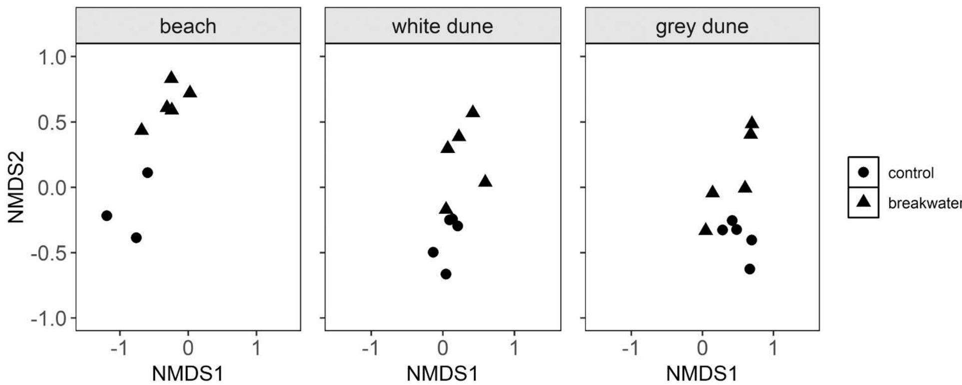

Fig. 3. Non-metric multidimensional scaling (NMDS) of the species-resolved vegetation coverage and on beach, white and grey dune at the control and breakwater site. The stress value for the calculation of the non-metric multidimensional scaling (NMDS) was 0.111, the stressplot showed R2 values of 0.988 (non-metric fit) and 0.915 (linear fit). Analysis of similarity (ANOSIM) had a significance value of 0.001 and an R value of 0.564. Number of replicates was n = 5.

with a breakwater and the control site. The overlapping increases at the grey dune, indicating that the species composition and coverage is very similar at both sites. The stress value for the calculation of the non-metric multidimensional scaling (NMDS) was 0.111, the stressplot showed R^2 values of 0.988 (non-metric fit) and 0.915 (linear fit). The analysis of similarity (ANOSIM) showed a significance value of 0.001, and an R value of 0.564, based on the grouping by environments and sites.

3.3. Aquatic vegetation

Only presence-absence-data was collected for the vegetation analysis (Fig. 4). At the control site, either only seagrass (*Zostera marina* Linnaeus) was detected or no macrophytes at all.

The highest number of macroalgae was found on the revetment (12 species), followed by the seaward side of the breakwater (83 m, 8 species). On the landward side of the breakwater one species less was found (77 m, 7 species). Several species were found at two or all three sides: *Ceramium deslongchampsii* Chauvin ex Duby, *Vertebrata fucoides* (Hudson) Kuntze, *Fucus spiralis* Linnaeus, *Pylaiella littoralis* (Linnaeus) Kjellman, *Acrosiphonia arcta* (Dillwyn) Gain, *Ulva compressa* Linnaeus, *Ulva flexuosa* Wulfen and *Ulva intestinalis* Linnaeus. Particularly noteworthy are species that only occurred at one site. At the revetment these are: *Polysiphonia stricta* (Mertens ex Dillwyn) Greville, *Ectocarpus siliculosus* (Dillwyn) Lyngbye, *Spongonema tomentosum* (Hudson) Kützing, *Acrosiphonia sonderi* (Kützing) Kornmann and *Ulva prolifera* O.F.Müller. At the landward side of the breakwater these are: *Furcellaria lumbricalis* (Hudson) J.V.Lamouroux and *Ulva linza* Linnaeus. At the seaward side of the breakwater these are: *Rhodochorton* sp. Nägeli.

The similarities concerning the distribution of these algae species are shown in Fig. 5. Sites with similar species composition are located closer to each other than to locations with a differing algae species composition. There is minimal overlap between the three sites. Both sites of the breakwater (landward = 77 m, seaward = 83 m) have the most dissimilarities. The revetment is equally similar to both sites of the breakwater. The stress value for the calculation of the non-metric multidimensional scaling (NMDS) was 0.048, the stressplot showed R^2 values of 0.998 (non-metric fit) and 0.983 (linear fit). The analysis of similarity (ANOSIM) showed a significance value of 0.001, and an R value of 0.684, based on the grouping by environments and sites.

4. Discussion

If effective, coastal protection measures should alter habitats – at least during extreme events. Since coastal ecosystems are dynamic ecosystems undergoing successions, sometimes repeatedly after disturbances, these alterations of habitats could be displayed by its characteristics. Reasons for that are either changes in the frequency or amplitudes of the disturbances or because the complexity of parameters in the habitats changes as well. Our results show that both can be the case and the extent to which sediment characteristics change along coastal sections with breakwaters, revetments or not protected sections,

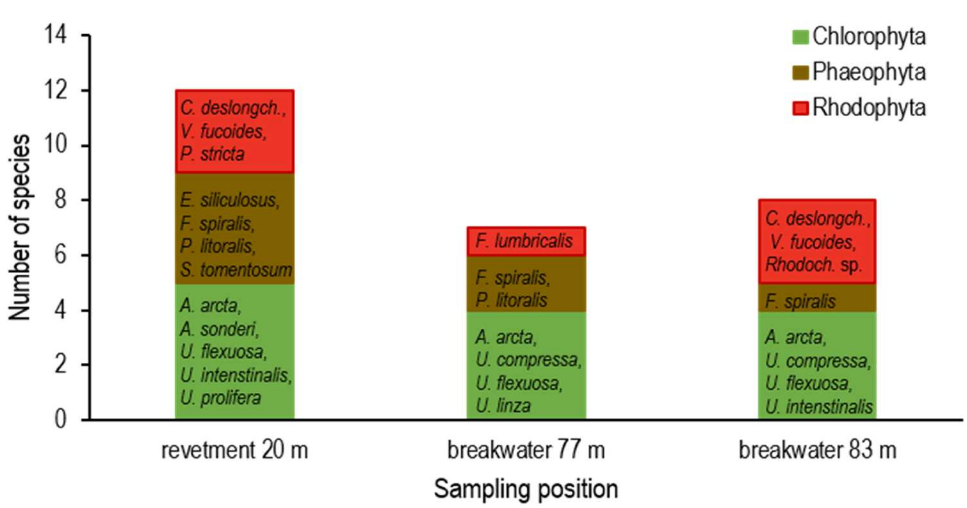

Fig. 4. Number of algae species found at revetment (20 m), landward site of the breakwater (77 m) and seaward site of the breakwater (83 m). Stacked bar charts are divided in Chlorophyta, Phaeophyta and Rhodophyta. Algae species are listed in bar charts for each sampling position.

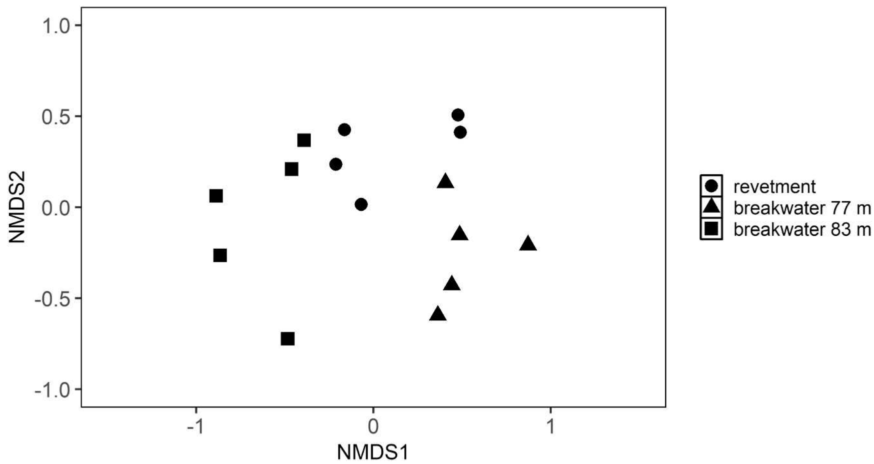

Fig. 5. Non-metric multidimensional scaling (NMDS) of the algae species composition at the revetment and breakwater site (both landward = 77 m and seaward = 83 m). The stress value for the calculation of the non-metric multidimensional scaling (NMDS) was 0.048, the stressplot showed R2 values of 0.998 (non-metric fit) and 0.983 (linear fit). Analysis of similarity (ANOSIM) had a significance value of 0.001 and an R value of 0.684. Number of replicates was n = 5.

answering hypothesis (i). Breakwaters are already known to cause changes in sediment parameters on a possibly long-term and wide-scale basis including the sedimentation of finer sediments (Airoldi et al., 2005; Moschella et al., 2005). The reasons lie in the construction of the breakwaters and their function in reducing the physical energy of incoming waves and water movement, or even accumulation of sediment near the coast. This results in modified hydrodynamics dominated by calm wave patterns and an overall reduced current on the landward side of a breakwater (Martin et al., 2005). Other artificial structures, such as revetments, can influence the wave regime, hydrodynamic circulation and the sediment transport in shallow coastal waters too (Ariffin et al., 2018). Both breakwaters and revetments have a greater impact in areas where soft sediment dominate (Nordstrom, 2000). This situation influences the spatial distribution of sediment types (Rosenberg, 1995)

These changes apply especially for the shallow waters in front of the revetment or in between the breakwater and the beach, whereby the latter can be seen in Thiessow with significantly smaller mean grain sizes. Most of these finer particles seem to be of organic material, as there was also an increase of organic content in those parts. An increase in organic content in shallow waters near the breakwaters was reported by Airoldi et al. (2005) too. If the accumulation of fine, organic particles exceeds certain amounts or causes anoxic conditions in the already highly modified habitat, the abundance of benthic invertebrates can be negatively influenced (Martin et al., 2005). Possibly, the growth of seagrass could also be influenced, although this has not yet been investigated. But these alterations are limited on a spatial scale (Martin et al., 2005).

In contrast to this, no accumulation of finer sediments or even organic contents was measured in front of the revetment. Even more, the sediment grain size increased in size in close proximity to the revetment as this coastal structure prevents erosion by armoring the coastline possibly even increasing high energy wave patterns (Chapman and Underwood, 2011). As these effects are mostly driven by a modified hydrodynamic situation, they do not reach the terrestrial part leading to an almost identical sediment composition at the dune and beach at all sites.

The water content in the sediments in coastal areas is mostly influenced by factors such as rainfall or groundwater discharge. As the sediment samples for the analysis were only taken from the upper most 20 cm of the beach and dune outside of the intertidal zone, groundwater discharge can be excluded as a potential influence on the data (Ehlert von Ahn et al., 2024). The influence of precipitation is also unlikely due to the spatial and temporal design of the sampling. Still, at the breakwater site a significant higher water content was measured at the beach and a significantly lower content at the dune in comparison with the control site. We therefore assume that these alterations are caused by the coastal protection measure.

Besides water content, the availability of nutrients determines the overall status of an ecosystem. Natural sources of nutrient input in terrestrial sediments in coastal ecosystems are sea spray (Holton, 1980) and beachwrack (Van Egmond et al., 2019), but overall the nutrient availability on the beach and dune is low compared to ecosystems with more fertile soils (Olff et al., 1993). This low phosphate availability, but also the high buffering capacity, favors plant species that have adapted to these conditions (Pit et al., 2020). Therefore, nutrient additions to these ecosystems can be seen as a major interference with the natural low nutrient conditions. Hence nutrient addition is likely to have an impact on plant communities, e.g., a shift in species composition or increased plant biomass after the addition of nitrogen (Van Wijnen and Bakker, 1999). The germination and growth of seedlings can be significantly increased by fertilization too (European Commission, 2004; Martin et al., 2005).

There are a few dune plants present on both mapped dunes, such as *Ammophila arenaria* (Kollmann et al., 2019), *Hieracium umbellatum* (Weigelt et al., 2005), *Lathyrus japonicus* (Walmsley and Davy, 1997) and *Leymus arenarius* (Greipsson and Davy, 1997). Other plant species only colonise certain successional dune stages. This can be influenced by coastal protection if an acceleration or inhibition of the successional process is initiated. Therefore, changing abiotic habitat conditions caused by coastal protection are reflected in the abundance and distribution of certain plant species. Some plants profit from habitat conditions at the breakwater site. One of these species is *Artemisia maritima* which is known to profit from higher nutrients (Van Wijnen and Bakker, 1999) and indicates for habitats with a vegetation community that develops towards more ruderal plants representing the more latter part of dune development (Lee et al., 2020). Similar results were noticed for *Honckenya peploides* (Houle, 1997). Other species indicate an advanced dune succession too: *Cerastium holosteoides* prefers stabilized dunes (Luzuriaga and Escudero, 2008), *Taraxacum* sp. the more inland side of fixed dunes (Ford, 1985) and *Senecio* sp. is generelly more abundant on undisturbed dunes (Vestergaard, 2008). Other species not only prefer, but can only be found in habitats well advanced in dune succession, in this case the breakwater site. This is the case for *Arrhenatherum elatius* which prefers fixed habitats (Pakeman et al., 2017), similar to *Lactuca tatarica* which is commonly found on low-energy coasts (Krisch, 1989). *Rumex crispus* which was found at the breakwater site, shows greater seed emergence at the landwards dune (Walmsley and Davy, 1997).

Calystegia soldanella usually acts as a sediment stabilizer of embryo dunes and was therefore abundant on the breakwater site (Zuccarini et al., 2016). *Phragmites australis* is typically growing in meadows or marshs (Landi and Angiolini, 2015) and *Geum urbanum* is more common in forest habitats (Verheyen and Hermy, 2001). The latter prefers nutrient rich, wet and semi-shady habitats and is not adapted to saline stress (Lauber et al., 2018), but a small population was still found at the breakwater dune.

Some plant species were only found on the control dune transects. One of those was *Cakile maritima*, a summer annual growing in beach-wrack piles (Kollmann et al., 2019) which were absent at the breakwater site. *Carex arenaria,* a very typical dune species that can grow well under dynamic conditions due to nutrient transfer through the roots was also only found at the control dune (D'Hertefeldt et al., 2011). *Galium mollugo* was only present on the control dune due to the absence of tall plants as overshadowing negatively effects the growth of this species (Meunier and Lavoie, 2012): at the breakwater site, the taller species *Phragmites australis* was present in larger quantities causing large-scale shadowing.

To summarise, the breakwaters cause accelerated dune succession towards a more stabilized dune habitat. This results in a greater plant diversity, a slightly different plant species composition with more meadow- and brown dune vegetation being identified compared to the part inside of the control region.

Underwater, algae can be used as indicators of ecosystem changes (Omar, 2010) due to their rapid reproduction rate, sensitivity to pollutants and accumulation of these.

The introduction of hard substrates on a previously sandy bottom, such as breakwaters and revetments, created artificial hard-bottom habitats (Airoldi et al., 2005; Martin et al., 2005; Moschella et al., 2005). In this study, this resulted in the establishment of algae on these surfaces. We observed an overall increase in macroflora diversity and biomass in the areas with coastal protection structures, consistent with Martin et al. (2005) and the European Commission (2004). However, the overall macroalgae diversity was still quite low, similar to Vaselli et al. (2008) and Moschella et al. (2005) observed, with 16 different taxa out of 192 taxa recorded in the Arkona Basin (Helsinki Commission, 2012).

Our NMDS and ANOSIM analysis revealed a significant divergence in macroalgae composition (Fig. 5) between the seaward and landward sides of the breakwater. This is confirmed by other studies (Airoldi et al., 2005; European Commission, 2004; Martin et al., 2005; Moschella et al., 2005; Vaselli et al., 2008). The algae composition on the revetment was similar in its algae composition to both sides of the breakwater. The total number of macroalgae was not substantially different between the revetment and the breakwater, presumably due to their close proximity, minimal depth difference and comparable structure. The majority of detected species were chlorophyte (Fig. 4). This abundance of chlorophyte may be attributed to the generally shallow depth of the structures, where a high percentage of sunlight penetrates the water column, favouring green algae (Vaselli, 2008). *Fucus spiralis*, was found on every sampling point and belongs to the Phaeophyta, a phylum of algae which are abundant in cold water ecosystems. *Fucus* sp. often inhabits intertidal zones (Nielsen and Lundsteen, 2019). In contrast to Martin et al. (2005), branching algae were not absent on the breakwater, but his study was conducted in Catalonia, Spain in the Mediterranean Sea under different conditions. Filamentous algae even dominated the macrophyte composition at the seaside of the breakwater (83 m), contrary to findings by Vaselli et al. (2008) and Airoldi et al. (2005). These algae thrive in polluted and nutrient enriched waters, which are often coastal ecosystems, created by coastal runoff and trapped organic material, for example by breakwaters (Airoldi et al., 2005; Lalli and Parsons, 1997; Lata Dora et al., 2010). The sampling method (scratch samples) might have contributed to these results, as only a fragment of the breakwater got sampled. Filamentous algae dominate the periphyton composition on the revetment as well, likely due to the close proximity to the nutrient-rich runoff near the shore.

Zostera marina was found only in the control transect. The breakwater seemed to have a repelling effect on *Zostera marina*, preventing its growth inside the breakwater basin and behind the breakwater (sampling spot "100 m"). The breakwater might have been inadvertently placed on a former seagrass patch, thereby burying the existing population. Alternatively, the breakwater may have attracted organisms that hinder the establishment of a seagrass population. Changes in currents, wave action, resulting in increased sedimentation, sediment composition and grain size could also have rendered the habitat unsuitable for *Zostera marina*. To determine the exact reason for the absence of seagrass further studies would need to be conducted.

The biodiversity of coastal dunes is evenly divided into primary dunes, white dunes and grey dunes (Acosta et al., 2009). It is therefore important to preserve all three ecosystems in order to maintain biodiversity. Natural disturbances, e.g. by regular washovers or wind blowouts, can even promote this (Ciccarelli and Bacaro, 2016). However, the functions of coastal ecosystems (ecosystem services) include more than just biodiversity, but also stabilisation of the coast which is the main goal of coastal protection measures. Therefore, the consequences of this coastal management on the ecosystem services can be described: the long-term stabilisation of the coastline through a one-time intervention can ensure an increase or preservation of biodiversity, but not necessarily with habitat-typical species. Stabilisation based on repeated interventions corresponds to an interruption of natural dune succession and can lead to a decline in biodiversity (Glueck et al., 2024).

Although the results showed significant differences between the three sites of the study, the limitations of the study must be taken into account here. The sites were not only strongly influenced by the different coastal protection measures, but other factors too, such as the north-south gradient. Nevertheless, the construction of breakwaters and revetments in Thiessow indicate that without coastal protection measures, severe erosion would dominate the area. It can therefore be assumed that the differences caused by the breakwater are greater than the differences caused by the orientation of the coastal section, but not all changes can be clearly attributed to the coastal protection measures.

5. Conclusion

In this study, we assessed the ecological impact of coastal protection structures, particularly breakwaters and revetments, on the coastline of Rügen, Germany, by directly comparing a modified coastline with an unmodified one. The results are conclusive: introducing hard structures on a sandy bottom results in a complete transformation of habitat properties, creating a distinct environment with different species. This supports the already reported changes of habitats characteristics in highly protected coastal zones. The ecological importance of coastal areas around the world is well known, but for the Baltic Sea there have been no detailed studies yet describing this aspect of human intervention in these systems. This study should close the information gap and provide interested stakeholders with a basis for future decisions, concerning coastal protection on the Baltic Sea coast as the results indicate possible effects of implementing coastal protection measures. Undesirable consequences can only be compensated for, but not prevented with the measures currently in use. The results presented here only represent the starting point for possible further analyses, which are necessary to map the exact and far-reaching consequences.

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CRediT authorship contribution statement

Anne Herbst: Writing – review & editing, Visualization, Validation, Software, Formal analysis, Conceptualization. **Hendrik Schubert:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Daniela Glueck:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nina Feußner:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Data availability

Data will be made available on request.

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Publication IV: Changes in sediment properties after a sand nourishment at the German Baltic Sea coast

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Changes in sediment characteristics after a sand nourishment at the German Baltic Sea coast

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Impact statement

As coastal communities face growing threats from sea level rise and storm surges, sand nourishment has become a widely used tool to protect shorelines. At the German Baltic Sea coast and many other coastal regions, this involves regularly dredging sand from the seafloor and depositing it on eroding beaches. While this approach offers immediate protection, its repeated use raises concerns about long-term impacts on coastal ecosystems. This study provides critical new insights into how sand nourishment alters the physical and chemical makeup of beach sediments and affects water turbidity. By tracking changes before and after a nourishment event over two years, the research shows that even short-term interventions can lead to measurable changes in sediment composition and prolonged turbidity in coastal waters. The broader relevance of these findings lies in their application to sustainable coastal management. As nourishment projects are expected to increase in frequency due to climate change, understanding their ecological footprint is essential. This research supports more informed decision-making by showing when and where impacts occur, how long they last, and what processes drive them. By highlighting the environmental costs of sand nourishments, the study encourages a more balanced approach to coastal protection. The insights gained can inform future nourishment designs, regulatory guidelines, and restoration efforts in coastal areas across Europe and beyond.

ABSTRACT

Sand nourishments are a common coastal protection measure in Germany and used to restore eroding beaches and dunes to protect the hinterland from floods. However, the nourishing of dredged marine sand to the coast poses the risk of drastically and repeatedly changing ecosystems. To estimate the temporal and spatial influence of such measures on the local sediments and the water column, sediment characteristics (D_{50}, sorting grade, and water, organic and carbonate contents) were measured before and after a nourishment event during a two year campaign. Additionally, water samples were used to determine the extent of the turbidity plume caused by suspended sediment. There were significant differences concerning the organic content in the sediment, a significant increase in water content and a decrease in carbonate content. However, most of the differences were only measurable for a few months. The turbidity plume was still present after three months. The main reasons for these changes are the

processes of dredging and dumping during the nourishment and the characteristics of the nourished marine sands. It can be assumed that the constant repetition of the sand nourishment every few years has a greater impact on the ecosystem than the individual nourishment.

Keywords: Turbidity, total suspended sediment, Baltic Sea, coastal protection, nature-based

Introduction

People need protection from rising sea levels as long as they want to live close to the coast. However, conventional hard structures do not offer the opportunity to cope with rising sea levels as the heightening and widening of these structures becomes unsustainable in an attempt to keep up with the increasing flood risk. The task of nature-based solutions is therefore the protection of coastal communities and the integrity of ecosystems in the context of rising sea levels and a limited budget. Some nature-based solutions can replenish existing coastal protection structures, e.g. by renaturation of coastal marshes and seagrass meadows (Temmerman et al. 2013). Other nature-based solutions, such as ecologically compatible sand nourishments and reinforcement (Pontee et al. 2016), ecologically favourable hard protection structures, retreat from coastal areas and managed realignments (Chausson et al. 2020), are even alternatives to conventional structures. It is generally agreed that sand nourishments are an nature-based solution for coastal protection, as they mimic natural processes (Pontee et al. 2016, Silva et al. 2014). This term refers to the erosion and sedimentation of cliff sediment that provides adjacent sandy beaches with sediment (Davidson-Arnott et al. 2019). However, by protecting cliffs with hard solutions to prevent coastal retreat, the cliffs are inactivated and cannot provide beaches close to the cliffs. This can cause sediment loss and a retreating coastline on sandy shores (Furmanczyk et al. 2011, Orviku et al. 2009) and thereby increase the risk of dune breach. Especially in areas where dunes are the only coastal protection, preventing a dune breach to reduce the risk of storm surges and floods in the coastal hinterland is important.

Ecological factors, e.g. saline inputs and sand dynamics, drive dune succession. Therefore, dune formation occurs at wind-exposed sides along the coast, whereas the wind-protected sides foster the development of salt marshes. Different vegetation zones develop due to the decreasing intensity of ecological factors with increasing distance from the shore. The sediment of coastal dunes is generally low in nutrients and has a high calcareous content and a low water holding capacity (Kollmann et al. 2019). As the soil develops, the nitrogen and carbon contents increases as the pH decreases (Ellenberg 1996). Dunes have several ecologically valued functions such as providing habitats for plants and animals. This caused the protections of almost all dune habitats within the framework of the annex 1 of the FFH-directive in the European Union (Kollmann et al. 2019).

But dunes are also an important part of coastal protection. Different measurements have been taken to nourish eroding dunes and sandy beaches. Dredged marine sands are used for replenishing the sand budget of the beach, in the supralitoral zone before the shoreline or as dune reinforcement (Nordstrom et al. 2004). Nevertheless, introducing systematic sand management to coastal systems can also cause negative effects or problems, e.g. coastline retreat. This is a result of changes in natural dynamics (Lammerts et al. 2009). Lammerts et al. (2009) also reported that allowing natural dune dynamics promotes coastal protection even better than the fixation of the dune. Beach nourishments can also impose risks in disturbing natural habitats, e.g. in the shallow water before the beach and dune endangering seagrass meadows and leading to a loss or reduction of this habitat type (Aragonés et al. 2015, Pagán et al. 2016, Pagán et al. 2018). Other large-scale ecological consequences at the nourishment site could potentially occur concerning the dune succession since alien sediments are introduced into ecosystems. These marine sediments exhibit characteristics typical of marine sea bottoms and are distinct from nutrient-poor beach and dune ecosystems. This leads to changes in vegetation characteristics and nutrient concentrations (Glueck et al. 2024).

Additionally, the extraction of sediments at the donor site of the nourishment implies the loss of habitat. Several noteworthy studies have demonstrated that it takes months to years until the conditions prior to sediment extraction at the donor site are met again (Krause et al. 2010, Mielck et al. 2019, Szymelfenig et al. 2006, Uścinowicz et al. 2014). The system's regeneration relies on the method of extraction. Large spatial scale dredging creates fewer deep sediment funnels that can replenish faster than dredging only a limited number of funnels (Staudt 2019, Staudt et al. 2021). The findings from these studies indicate a variety of factors that can also be associated with the coastal part of the ecosystem, such as turbidity plumes and changes in sediment parameters. The destruction of benthic habitats and local conditions could lead to changes in the local biotic community but also has an impact on predators (fishes, sea birds and marine mammals). However, there are only limited amounts of data describing coastal changes (Chiva et al. 2018, Colosio et al. 2007, Herman et al. 2021, Jackson et al. 2010, Pupienis et al. 2014).

Therefore, the central questions this research aims to answer are as follows: (1) how do sand nourishments affect coastal ecosystems and (2) can a nourished site return to site-specific sediment conditions or will the nourished sediment dominate the habitats until a new state of equilibrium is reached? This study will address the hypothesis that it takes several months until the sediment conditions prior to the nourishment are achieved again.

Materials and methods

This case study focuses on Ahrenshoop (Figure 1), a municipality located at the Darss-Zingster-Boddenchain, Germany, with access to both the Bodden and the Baltic Sea (54° 22' 50.573" N 12° 25' 16.506" E). The region is described as the bodden compensation coast, consisting of island cores and narrow land bridges (StAUN MM 2009). The predominant wind direction is from south-west to north-west with a wave climate ranging between wests to north-west. Low pressure areas are coming from north-west and can reach wind speeds of around 10 m/s and wind gusts of more than 20 m/s (DWD Climate Data Center 2023). Ahrenshoop is endangered during storm floods since the exposed coast of the Baltic Sea experiences a high alongshore sand transport which needs to be compensated for by beach nourishments that take place every few years (Kortekaas et al. 2010). The sediment supply for Ahrenshoop was originally ensured by eroding cliffs located south-west of the coast in Ahrenshoop which are protected by breakwaters now. An additional breakwater acts as a sediment trap right before the coastal stretch. This leads to a missing sediment supply in Ahrenshoop resulting in a receding coastline.

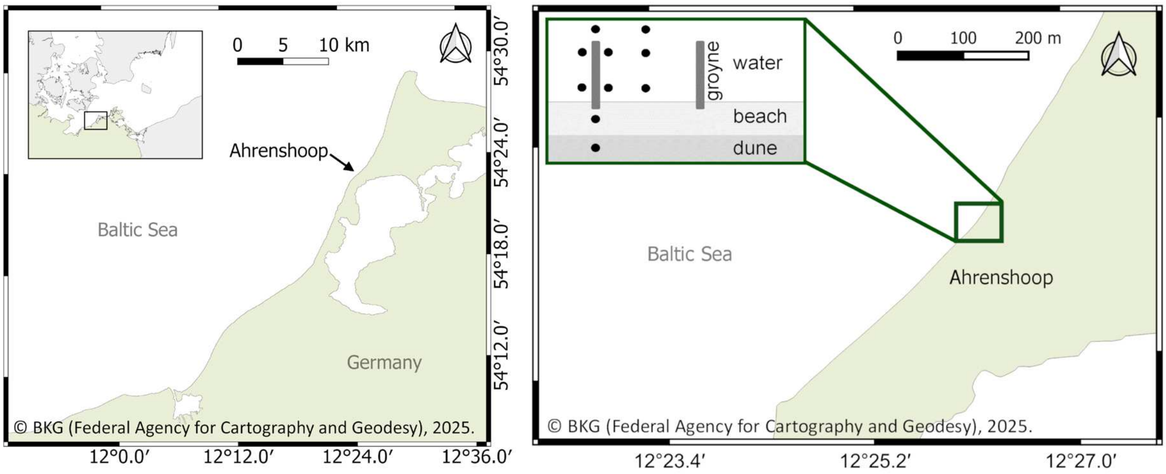

Figure 1 The sampling location was Ahrenshoop at the German Baltic Sea coast. There were in total 20 submerged stations sampled during the monitoring as well as five terrestrial stations which consisted each of ten substations.

During the last nourishment in the winter 2021/22, approximately 600 thousand cubic meters of sand were nourished onto the beach and dune at a total length of 4 km. For the nourishment, the dredging vessel flushed sediment and water through a duker onto the beach. Heavy machinery formed new shapes and slopes of dunes and beaches through the distribution of sand. The targeted dune crest height was 5 m with a seaward dune foot height of an additional 2 m. The inclination of the seaward slope was 1.3, the beach slope was 1.25 and the underwater slope was 1.3. After the nourishment, surface protection via the planting of more than 50,000 m² of marram grass *Ammophila arenaria* was performed. To determine the effects of such a measure, a two-year campaign was developed to analyse both short-term and long-term aspects. Before the nourishment, the condition of the ecosystem was analysed. This included taking sediment cores along the coastline at both the beach and dune locations (with five replicates, n = 5, sampling on 11.08.2021), shown in Figure 1. The next samples were collected in the following order: during the sand nourishment (25.11.2021, 11.01.2022 and 10.02.2022), one week after the nourishment (16.02.2022; only sediment samples), one month after the nourishment (water samples on 10.03.2022; sediment samples on 14.03.2022), three months after the nourishment (water samples on 16.05.2022; sediment samples on 19.05.2022), six months after the nourishment (sediment samples on 11.08.2022; water samples on 26.08.2022) and more than one year after the nourishment (water samples on 24.11.2022; sediment samples on 25.05.2023). All the samples were collected at least three days after the last rainfall in the area. For the coordinates of the sampling positions, see Supplementary Table S1.

Sediment analysis

The grain size distribution of a mixed sediment sample from the first 20 cm was determined after Schlungbaum (1979), the D_{50} (mean diameter of the grain) and the sorting grade after Sindowski (1938). The water content (relative wet weight in percent) was determined via Schlungbaum (1979) and the organic (relative dry weight in percent) and carbonate (relative dry weight in percent) content was determined via Czensny (1961).

Suspended sediment analysis

50 ml of each water sample was filtered through a glass fibre filter (pore size = 0.4 µm) to calculate the weight of the particles in the water sample, which was used to determine the total suspended sediment. The filters were dried (105 °C for 4 hours) and then burned at 550 °C for ignition loss.

Weather

Wind and wave data were retrieved from a weather station in Ahrenshoop (54◦ 23′ 19.741″ N 12◦ 25′ 54.800″ E) for the duration of the samplings from © Windfinder.com (2024). The significant wave height was calculated on the basis of Zanke (2013) for a period of four days, where the last day was the sampling day. Weather complications (heavy thunderstorms) led to shortened or cancelled samplings before the nourishment and one week after the nourishment for safety reasons. This resulted in missing data: the water samples at 2 m water depth (middle of the water column) before the nourishment and the water samples one week after the nourishment. The rainfall data was retrieved from the DWD Climate Data Centre (2023).

Statistics

For the statistical analysis, R statistical software version 4.0.3 was used. The water samples were analysed, after normality and variance homogeneity were checked, via ANOVA or the Kruskal-Wallis-Test with the sampling site as a factor. An additional test was necessary since the requirements for ANOVA were not met for all the parameters. Post hoc pairwise multiple comparisons were carried out via Dunn's test against an alpha-level of 0.05 to identify differences between the sampling times. The Spearman correlation test for turbidity and hydrodynamic conditions was performed with a p value of 0.05.

Results

Before the nourishment, the sediment parameters of the extraction site were measured. The water content was 8.658 ± 1.396% of the wet weight, the organic content was 10.090 ± 1.621% of the dry weight and the carbonate content was 0.501 ± 0.067% of the dry weight. The sediment was well sorted with a sorting grade of 1.388 ± 0.514 and a D_{50} of 0.270 ± 0.006 mmm.

Temporal development of sediment parameters at the nourishment site

Water content: There were significant differences between the sampling times at each station. At the beach and dune sites, the water content increased after the nourishment, but started to decrease after one month. At the submerged sampling stations, the water content decreased slightly after the nourishment. After six months, the water content was still lower than that before the nourishment. However, at most sampling sites the water content was similar to that before the sand nourishment after one year. The greatest differences in water content were measured in shallow water (0.5 m depth). The water content was lowest at three months after the nourishment and subsequently increased (Figure 2).

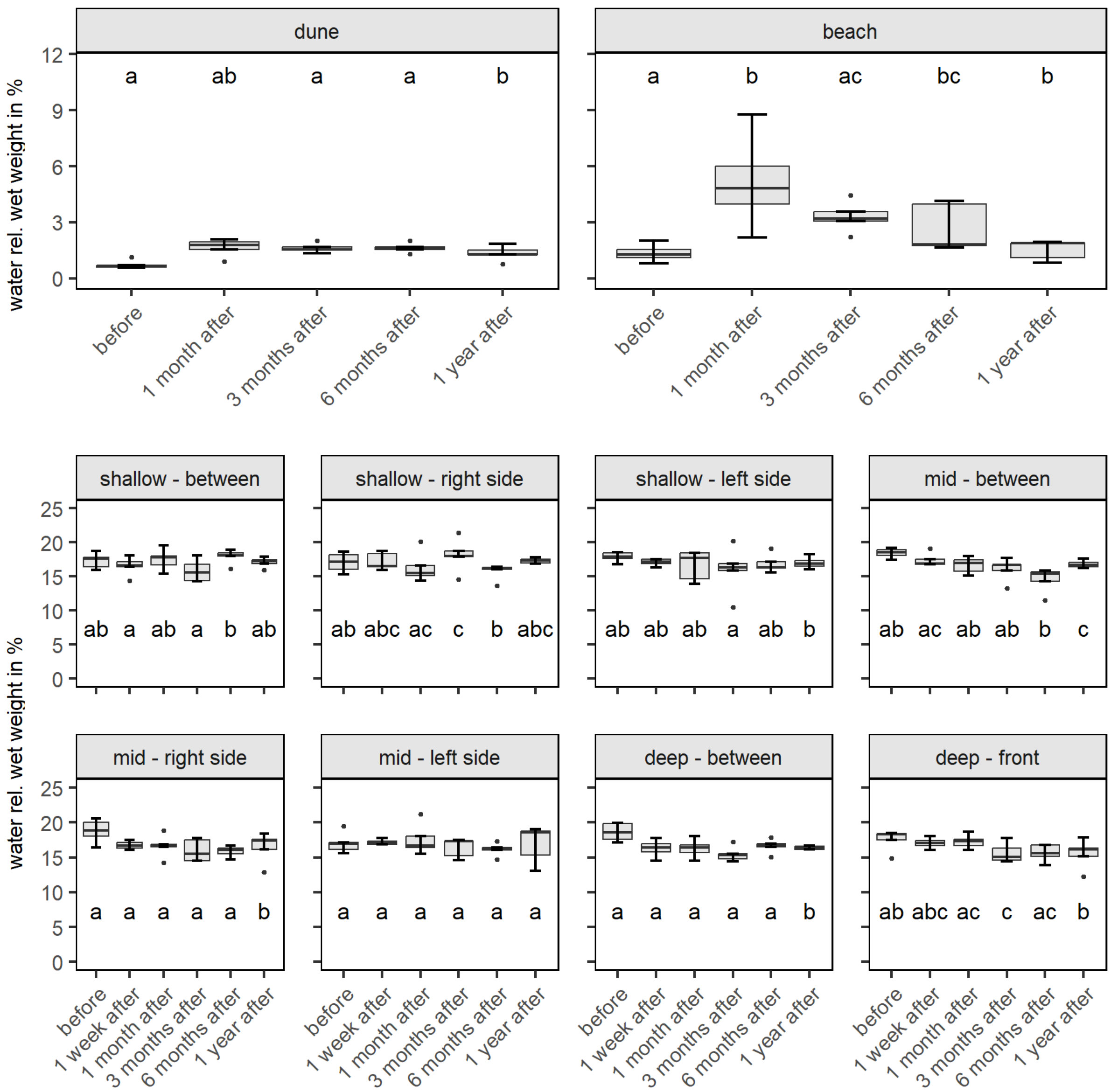

Figure 2 Temporal development of the water content (relative wet weight in percent) in the first 20 cm of the sediment at the nourishment site in Ahrenshoop (n = 5). The values presented in the box plots are medians (middle bars), and the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from five replicates. The box plots also include whiskers (representing 5 95% of the variability) and outliers (points). Different letters indicate significant differences between sampling times (Dunn's test, $P < 0.05$).

Organic content: There were significant differences between the sampling times at almost every station. Only the organic content at the terrestrial stations remained approximately the same. After the nourishment, the organic content at all the submerged stations decreased. The lowest organic content was detected one month after the nourishment, after which it slowly increased until one year. One year after the nourishment, the organic content was similar to that before the nourishment at some sampling sites, but not at all sites (Figure 3). In particular, in the shallow water zone, the content was still lower than before.

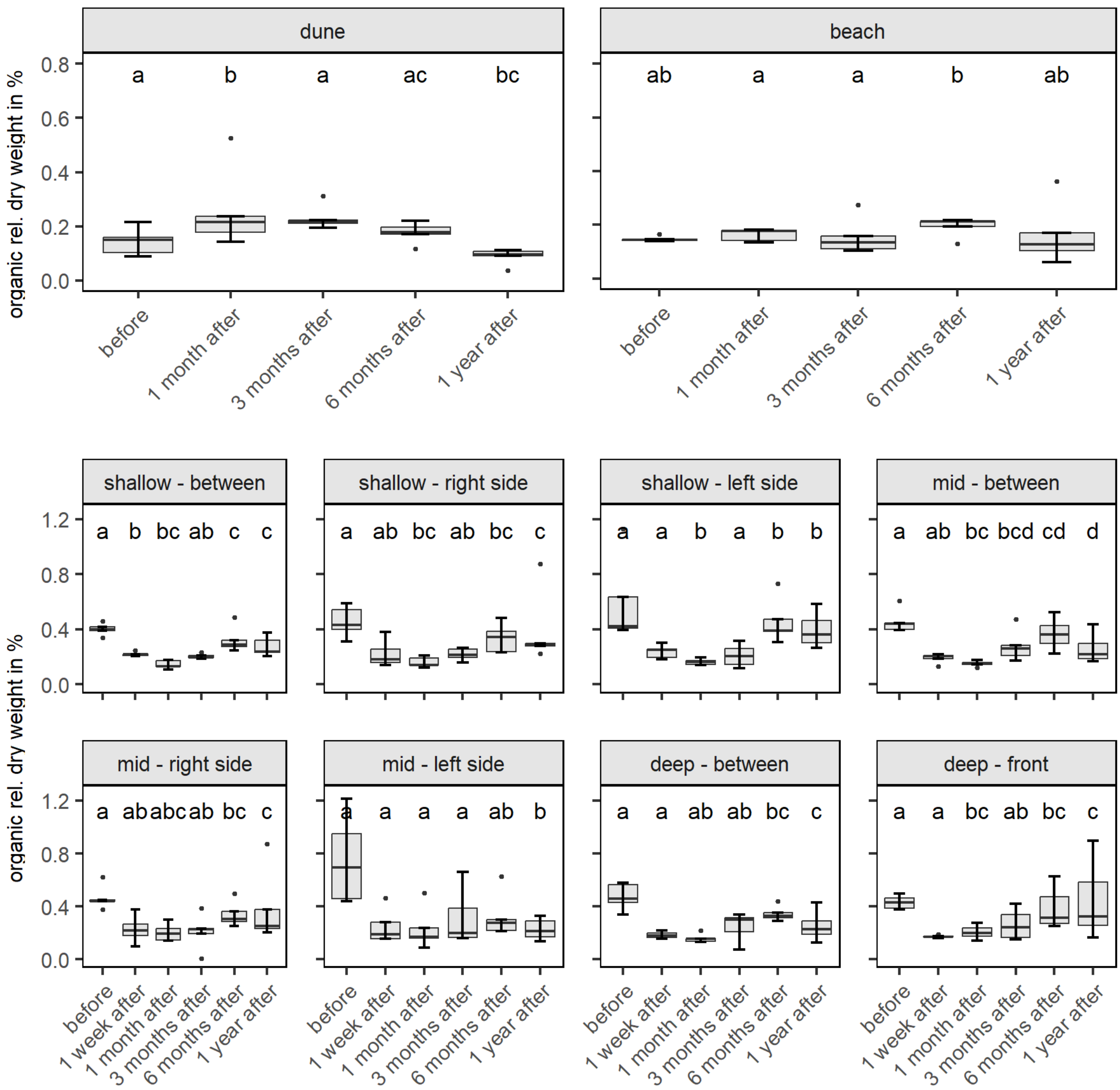

Figure 3 Temporal development of the organic content (relative dry weight in percent) in the first 20 cm of the sediment at the nourishment site in Ahrenshoop (n = 5). The values presented in the box plots are medians (middle bars), and the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from five replicates. The box plots also include whiskers (representing 5 95% of the variability) and outliers (points). Different letters indicate significant differences between sampling times (Dunn's test, $P < 0.05$).

Carbonate content: There were significant differences between the sampling times at each station, but the measured content already varied greatly between the replicates, especially at the submerged stations. In general, the carbonate content at all stations decreased slightly after the nourishment. The lowest carbonate content was measured after one month. After one year, the carbonate content was still lower than it was before the nourishment at some sampling sites (Supplementary Figure S6).

D_{50} and sorting grade: There were significant differences between the D_{50} and the sorting at different sampling times in Ahrenshoop. The D_{50} at the beach and the dune decreased after the nourishment, but remained the same at the submerged sampling stations (Figure 4). The results of the sorting grade analysis are consistent with those of D_{50}. The sorting grade differed significantly throughout the duration of the experiment. At most stations, the sorting grade increased after the nourishment and then decreased again (Figure 4). After one year, only the beach and the dune had a different sorting grade than before the nourishment. The other stations returned to the pre-nourishment state. Overall, the sediment at all the stations was very well sorted. Furthermore, the D_{50} and the sorting grade of all the stations are more similar to each other after the nourishment than before.

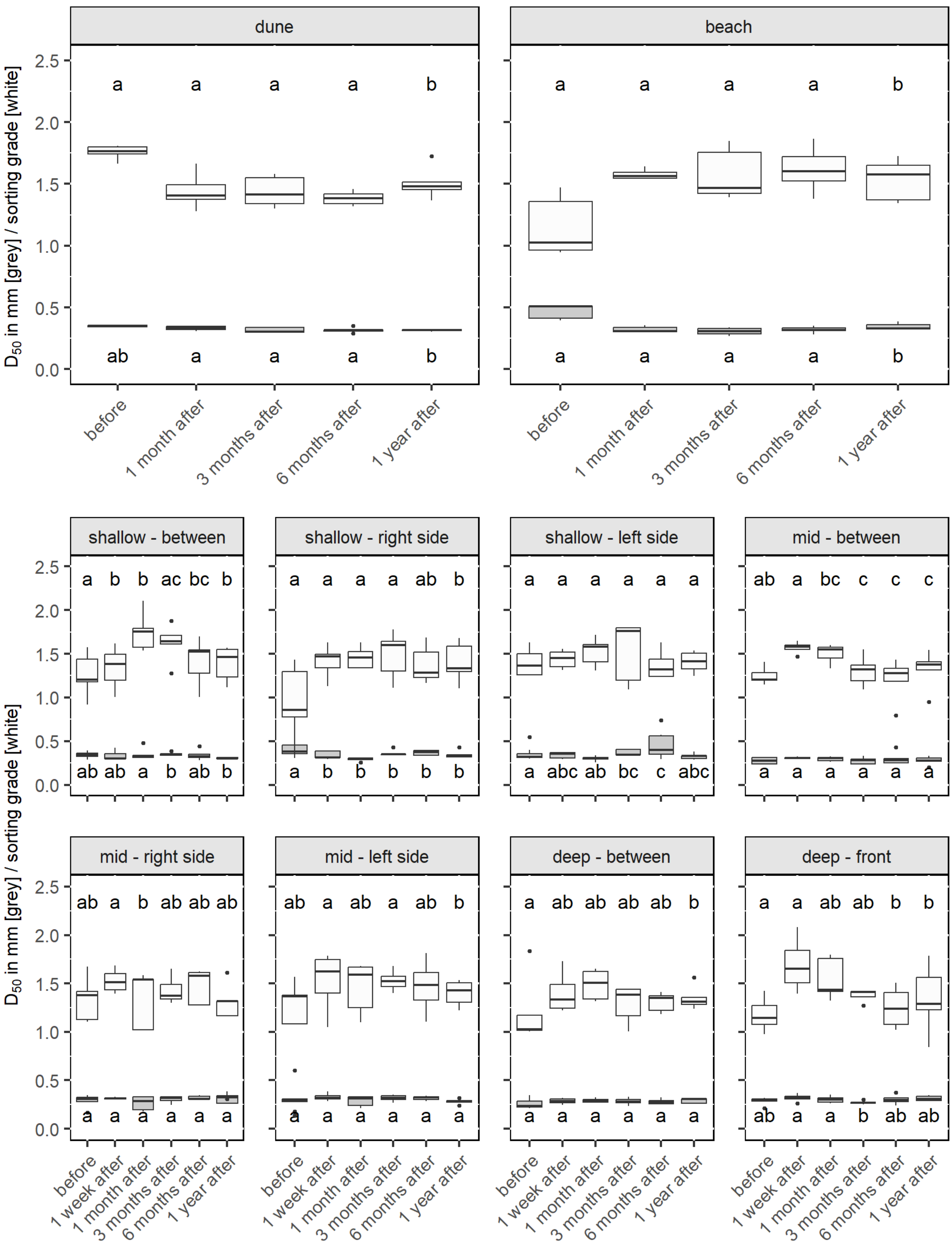

Figure 4 Temporal development of the D_{50} (in mm, grey box plots) and the sorting grade (white box plots) in the first 20 cm of the sediment at the nourishment site in Ahrenshoop (n = 5). The values presented in the box plots are medians (middle bars), and the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from five replicates. The box plots also include whiskers (representing 5 - 95% of the variability) and outliers (points). Different letters indicate significant differences between sampling times (Dunn's test, $P < 0.05$).

Wind and wave data

The wind and wave conditions were similar across all samplings (Supplementary Table S2). These weather conditions were ensured to be similar at least three days before the sampling day. There was no significant correlation between the wind and wave data, and the measured turbidity. The correlation indicated only limited relation between the weather data and the measured turbidity. There is a moderate correlation the wind speed (R = 0.59), but only a weak correlation with the wave period (R = 0.46) and no correlation with wave height (R = 0.16).

Temporal development of suspended sediment in the water column at the nourishment site

The amount of particles in the water column increased significantly during and after the nourishment. During the nourishment, there are up to four times more particles with a diameter greater than 0.4 µm than there were before the nourishment. One month after the nourishment, the amount of particles in the water column was still almost the same as that during the nourishment. Three months after the nourishment, the amount decreased. At one year, the amount is approximately the same as that before the nourishment (Figure 5). The proportion of organic matter in the particles remained approximately the same (Supplementary Table S3). There were no significant differences between the different sampling times during the nourishment.

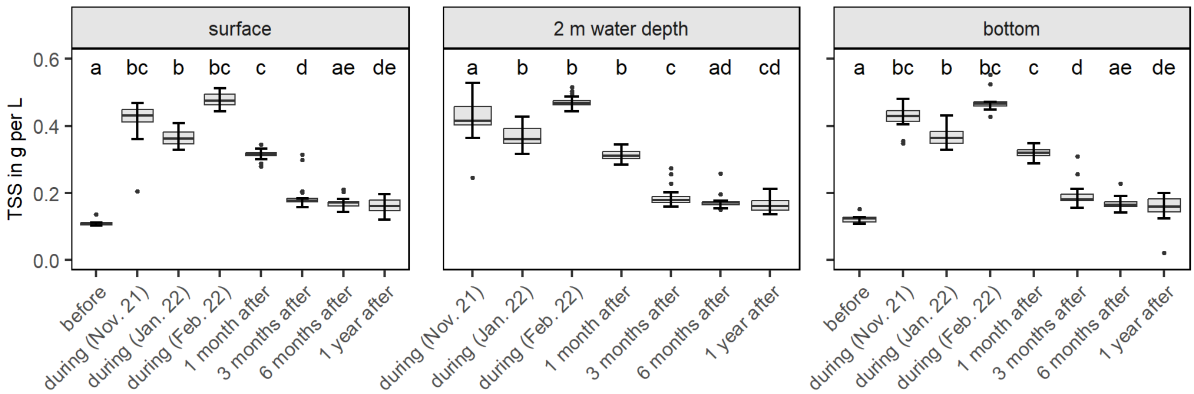

Figure 5 Dry weight of total suspended sediment (TSS) with a diameter > 0.4 µm in the water column in g per L at three different water depths (n = 20). The values presented in the box plots are medians (middle bars), and the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from five replicates. The box plots also include whiskers (representing 5 - 95% of the variability) and outliers (points). Different letters indicate significant differences between sampling times (Dunn's test, P < 0.05).

Discussion

It is generally agreed that the turbidity caused by a sand nourishment on a beach is only localized and transitory in comparison to sand nourishment actions offshore (Roman-Sierra et al. 2011, Wilber et al. 2006). While the larger particles of the sediment settle quickly, the finer particles require more time and can therefore be washed away by currents (Jordan et al. 2010). This is especially problematic if the nourished sediment consists mostly of conglomerates that can be broken into finer particles by waves and can remain suspended in the water column causing turbidity. Turbidity can decrease only when there are no more conglomerates present in the sediment that can be broken down (Chiva et al. 2018). In this context, waves have been shown to be the primary cause of turbidity at the bottom near waters via sediment resuspension (Capello et al. 2014, You 2005).

During this experiment, elevated turbidity was measured even 400 m away from the discharge pipe. The average particle concentration during the nourishment is approximately 0.4 g/L which is more than ten times the concentration were measured by other researchers (Capello et al. 2014, Roman-Sierra et al. 2011, Wilber et al. 2006). This is mostly because the basal turbidity in this part of the Baltic Sea is already higher than that in other oceans. Even without disturbances, the turbidity measured in the winter season was approximately 0.2 g/L (Glueck 2023). The particulate concentrations were homogenous in the water column during the sand nourishment as Capello et al. (2014) reported. The organic fraction in the turbidity plume was very low (Supplementary Table S3) because of the nourishment mechanism (Capello et al. 2014). After three months, most of the particles in the water column had settled.

The turbidity plume could also be caused by hydrodynamic conditions. The sand nourishment was performed in winter, which is the storm season in the Baltic Sea. During this season, the mean wind speed approximately 18 knots dominated the weather. Almost all wind directions occur, but southwest and west winds are measured more frequently (Tiesel 1995). The mean wave height between 1991 and 2020 ranged between 0.5 m and 1.0 m with the highest values measured in the winter season by the wave buoy “Darss Sill” on the Western Baltic Proper (Pettersson et al. 2022). The situation near the coast during the samplings was similar: both the days of the sampling and the period of at least three days before the sampling were taken into account. In the latter period, wind speeds above 10 knots were not reached and the wind and wave directions were similar to those on the sampling day. Nevertheless, there were some differences in the hydrodynamic conditions during the sampling days. This mainly concerned the wave period where the highest values were measured during the sand nourishment and the significant wave height. However, the hydrodynamic conditions were not significantly correlated with the total suspended sediment. The measured turbidity therefore appears to be independent of the wind and wave data analysed. This also becomes clear when comparing the graph depicting the total suspended sediments (Figure 5) and the tables containing the wind and wave data (Supplementary Table S2): the highest values for the wave period and wind speed were measured at the second sampling during the sand nourishment. However, this sampling resulted in the lowest concentration of total suspended sediment during the sand nourishment. The highest concentration of total suspended sediment values were measured at the third sampling during the sand nourishment, when the wave period and wind speed were lower. This is even more pronounced for the significant wave height calculated over a period of four days, with the last day being the sampling day. Here, the highest values were measured before the sand nourishment, but the concentration of total suspended sediment were significantly lower.

However, these differences were overshadowed by another very clear measurement result: control measurements carried out during storms. For safety reasons, these measurements could be carried out only from land, and only surface water was sampled. Nevertheless, the turbidity during these storms was significantly lower than that during the sand nourishment (Glueck 2023). Accordingly, turbidity during the sand nourishment can hardly be caused solely by hydrodynamic conditions that occur during the storm season in the Baltic Sea. Nevertheless, the duration of the turbidity plume can be influenced by wind and waves. Most of this turbidity is likely caused by the resuspension of finer particles, such as silt and schluff. The grain size < 200 µm made up 17 % of the nourished sediment but only 10 % were measured in the sediment cores taken on the beach and in the shallow water. Notably, the other 7 % were washed into the water body and have since been reworked. This can even increase local turbidity during storms (Nordstrom et al. 2004). Increased turbidity over a longer period can affect the organisms living in that area, e.g. a negative influence on the growth and abundance of invertebrates has already been reported (Manning et al. 2014, Roegner et al. 2021). To date, no reports have been published concerning the effects of sessile macrophytes. Since the nourishment at Ahrenshoop took place in winter 2021/2022, most turbidity was already gone when the annual macrophyte growth season started. Perennial algae and seagrass may have been disturbed by the increased turbidity.

Sediment parameters such as D_{50}, sorting grade and the different proportions of water, organic and inorganic compounds, play highly relevant roles in the ecology of an ecosystem. Especially in coastal habitats, they determine the stability of the system and can enhance or inhibit dune succession (Jackson et al. 2010, Pupienis et al. 2014, Zelo et al. 2000) and therefore the ecological value of the system (Nelson 1993). With this in mind, the sediment used in the recent beach nourishments is selected for its similarity to the sediment at the nourished site. The evidence from this study suggests that this selection was partially successful, especially concerning the mean grain size. Only at the beach and shallow water sampling stations, were there smaller changes most likely due to the dynamic state of the ecosystem, which can lead to the reworking of the sediment caused by waves. Similar results were reported by other researchers (Santos-Vendoiro et al. 2021), who reported that most changes in sediment parameters are the result of seasonal hydrodynamics (swell waves in winter and sea waves in summer). In other nourishments, there are differences between the nourished sediment and the native sediments at the beach (Pupienis et al. 2014). The particle size of the nourished sediment can modify the morphodynamic state of a beach (McLachlan 1996) and therefore influence the longevity of a beach nourishment (Eitner 1996). A sand granulometric composition mismatch can cause the disappearance of beaches in just two years after nourishing (van Duin et al. 2004). Nourishment of greater particle sizes can lead to the removal of finer sediments (Jackson et al. 2010, Chiva et al. 2018) and therefore affecting benthic assemblages too. Although the D_{50} was very similar in this sand nourishment, the sorting grade changed after the nourishment possibly causing the changes of the sandy-beach meiofauna in Ahrenshoop as already shown by Kapshyna et al. (2024). Additionally, other coastal protection measures have an impact on sediment parameters. Beach nourishments in combination with breakwaters create more stable habitats and can even cause the sedimentation of finer sediments (Colosio et al. 2007). These changes in sediment parameters can cause long-term and wide-scale effects. In Ahrenshoop, there are also groynes at the nourished sites. They could have a similar effect on the longevity of the nourishment since it takes at least five years until the beach disappears again and the next nourishment is planned.

The water content (Figure 2) changed after the nourishment mostly in the terrestrial habitats but returned to prior nourishment conditions within one year. This result can be explained by the mechanism used in the nourishment: the sediment that has been taken up by the nourishment vessel, is rinsed with water through a long pipeline to the beach. The sediment-water mixture is then distributed on the beach and the dune with heavy machinery. Due to the high water proportion in the sediment, it can take several weeks until the water content decreases to lower levels. Although the water content in the sediment in coastal areas is influenced by multiple factors, including rainfall and groundwater discharge, these factors do not need inclusion in this discussion. The main reason for this is the absolute prominence of the coastal protection measure which overlays all natural influences. The volume of water that was flushed into the coastal system within the short time frame of the nourishment exceeded possible levels of rainfall (Ehlin 1981). The nourished sediment is flushed through the pipelines in a mixture with water, the latter making up almost 70 % of the volume (Kortekaas et al. 2010). Since the nourishment included a sand volume of 600,000 m^3, a volume of 1 400 000 m^3 water was flushed onto an only 4 km long coastal section within three months. For comparison, the mean daily rainfall in this area was only up to 3 mm (Supplementary Table S4). Additionally, the sediment samples were taken from the uppermost 20 cm of the beach outside of the intertidal zone excluding possible groundwater discharge (Ahn et al. 2021). A high water content in beach and dune can lead to changes in vegetation composition. Most plants growing under coastal conditions are adapted to short term flooding but not for several weeks. A greater water content at the beach for several months can cause a shift in the species composition to better-adjusted species and therefore affect dune succession. Primary dunes can be vegetated by e.g. the flood and salt-tolerant *Leymus arenarius* instead of *Ammophila arenaria*. Pit et al. (2020) and Glueck et al. (2024) also reported a vegetation shift at the dune as an effect of nutrient addition.

The organic content also changed significantly after the nourishment. Apparently, the nourished sediment had a lower organic content than the sediment at the beach in Ahrenshoop. This is surprising, since the samples from the extraction had an organic content of approximately 10%. This indicates that the organic content of the sediment accumulated somewhere else. One possibility is the water body at the coast in Ahrenshoop. The organic content could have been flushed from the beach with water, since the mechanism of the nourishment itself is based on pumping a water-sediment-mixture through pipelines. While the sand settles on the beach, the remaining water flows down and takes the organic particles with it. However, the results clearly show that this is not the case (Supplementary Table S3). On the contrary, the proportion of particles consisting of organic matter remained similar throughout the entire experiment. This could mean that the organic content of the extracted sediment remained at the extraction site. The mechanism of the nourishment process is partly responsible for this since the uptake of the sediment is achieved by a suction dredger vessel. After extracting the sediment, the drain of excess water takes place before the vessel moves to the nourishment site (Capello et al. 2014). The organic content was thus removed from the sediment. Additionally, most of the organic content at the sediment deposition site forms a fluffy layer on top of the ocean bottom instead of being mixed in the sediment. This layer can be moved and dispersed by water motion. It is very likely that part of the fluffy layer already dispersed into the water column and thus was not sucked into the vessel. This finding is consistent with that of Colosio et al. (2007), who reported a lower organic content at coastal sites where sand nourishments occurred, with an average content lower than approximately 2 %. Sites with different kinds of coastal protection presented significantly higher organic contents. In this study, the organic content started to increase again after a few months, indicating an accumulation. This could be a result of micro- and macrobial activity breaking down larger pieces of organic matter to incorporate into the sediment. Additionally, at shallow water sampling sites, water movement (currents and waves) can reinforce the process and sediment mixing causes a distribution of organic material. After one year, the organic content measured in the sediment samples was almost the same as that before the nourishment for most sampling sites. At the terrestrial sampling sites, the organic content before the nourishment was even lower. The nourishment led to an increase but after one year, the content returned to conditions prior to the nourishment. This is again due to biological processes but in contrast to the submerged sampling sites, the organic content did not increase but was rather consumed.

The rapid decrease in carbonate content in the sediment samples is similar to the change the organic content and is a consequence of the use of the sediment with a low carbonate content for the nourishment and the nourishment mechanism itself. In this case, the carbonate content of the sediment was already low but even sediments with higher carbonate contents experienced a decrease. Since the carbonate content is mostly independent of biological processes, physical and chemical processes can change the content in the sediment. In the subtidal system, this can include water movement and dissolution. A high proportion of carbonates can influence their dissolution in water (Milliman 1993). Because these processes take more time than biological processes do, the carbonate content did not increase as quickly as the organic content did.

Conclusions

The sand nourishment caused several significant changes in the sediment characteristics of the nourished coastal area. However, most of these changes are only temporarily and the nourished site returned to site-specific conditions within a few months concerning the sediment characteristics and up to one year when talking about the turbidity. In addition to changing sediment parameters and turbidity, more environmental factors need to be considered to estimate the ecological effects of sand nourishments. These coastal protection measures can mimic natural processes but they do so in a very short time frame. There is no natural event where half a million cubic meters of sand are deposited at a beach. This additional sand deposition can lead to intensified sediment transport from the beach to the dune, e.g. through aeolian sand transport (Jackson et al. 2010). Too much deposition of sand drift at the dune can lead to the suffocation of dune-building plants (van der Wal 2004). Therefore, the impacts of such a nourishment are not limited to the exact site of the nourishment but can also be found in other environments. This leads to the conclusion that with this type of coastal protection, neighbouring ecosystems must also be monitored more closely in the future to limit the effects on the ecosystem services of habitats that are already under human pressure.

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Author contributions

Conceptualization: Daniela Glueck, Hendrik Schubert; Methodology: Daniela Glueck; Formal analysis and investigation: Daniela Glueck; Writing - original draft preparation: Daniela Glueck; Writing - review and editing: Daniela Glueck, Hendrik Schubert; Funding acquisition: Hendrik Schubert; Resources: Hendrik Schubert; Supervision: Hendrik Schubert

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Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article. The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Data Availability statement

The data that support the findings of this study are available from the corresponding author, D. Glueck, upon reasonable request.

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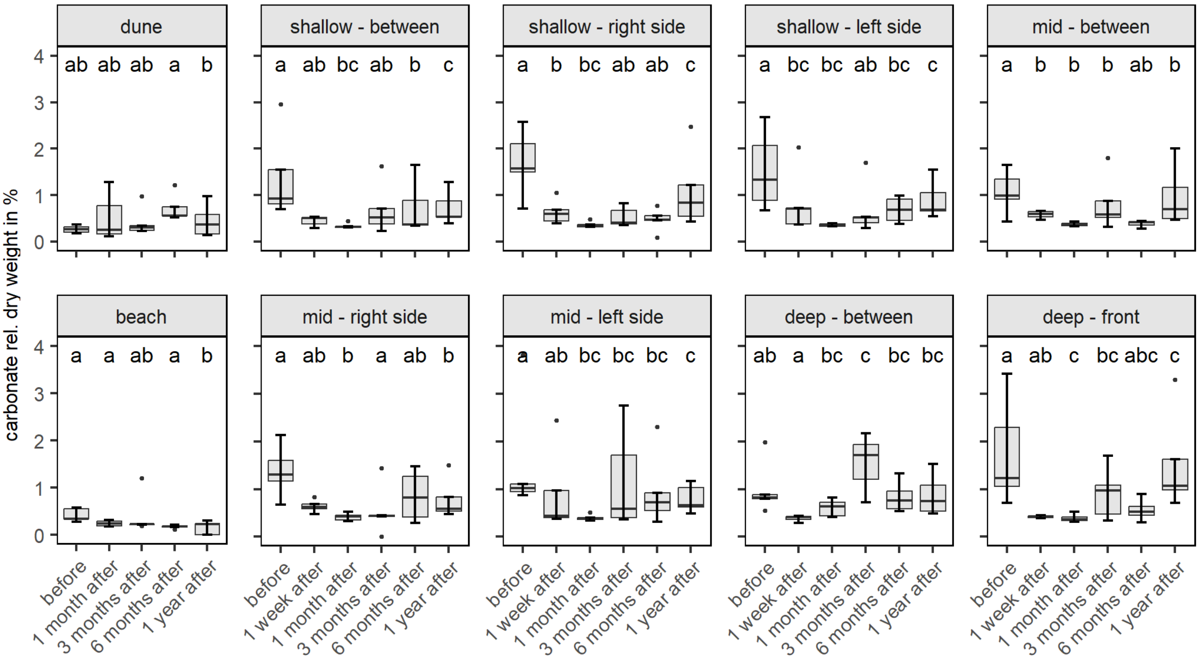
Supplements



Supplementary Figure S6 Temporal development of the carbonate content (relative carbonate dry weight in percent) in the first 20 cm of the sediment at the nourishment site in Ahrenshoop (n = 5). The values presented in the box plots are medians (middle bars), and the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) from five replicates. The box plots also include whiskers (representing 5 - 95% of the variability) and outliers (points). Different letters indicate significant differences between sampling times (Dunn's test, $P < 0.05$).

Supplementary Table S1 Overview and coordinates of all sampling stations in Ahrenshoop. Terrestrial sampling stations included 10 sampling sites around the groyne (submerged) and at the beach and dune. Water sampling stations included each three water depths (0 m, 2 m, and 4 m).

station	description	longitude (degrees east)	latitude (degrees north)
1	terrestrial station	12.412585	54.379401
2	terrestrial station	12.423363	54.384550
3	terrestrial station	12.430147	54.387658
4	terrestrial station	12.436670	54.391662
5	terrestrial station	12.443592	54.397573
6	water sampling station	12.405333	54.377983
7	water sampling station	12.413367	54.383167
8	water sampling station	12.422000	54.388250
9	water sampling station	12.432767	54.394283
10	water sampling station	12.441500	54.399317
11	water sampling station	12.404300	54.378533
12	water sampling station	12.412133	54.383967
13	water sampling station	12.420900	54.388850
14	water sampling station	12.431450	54.394950
15	water sampling station	12.439867	54.399850
16	water sampling station	12.403217	54.379100
17	water sampling station	12.411033	54.384417
18	water sampling station	12.419533	54.389400
19	water sampling station	12.430083	54.395350
20	water sampling station	12.438333	54.400300
21	water sampling station	12.402217	54.379667
22	water sampling station	12.409833	54.385067
23	water sampling station	12.418417	54.389900
24	water sampling station	12.428883	54.395800
25	water sampling station	12.436783	54.400650

Supplementary Table S2 The wind and wave data (wind speed in kts, wind direction in degree, wave height in m, wave direction in degree, wave period in s and significant wave height in m) at the water sampling days. Shown are mean values ± standard deviation (except significant wave height).

	wind speed / kts	**wind direction / degree**	**wave height / m**	**wave direction / degree**	**wave period / s**	**significant wave height / m**
before (14.10.2021)	2.3 ± 0.7	253.5 ± 10.7	0.2 ± 0.0	317.5 ± 21.6	4.3 ± 0.5	0.7
during (25.11.2021)	3.3 ± 0.9	227.2 ± 9.0	0.3 ± 0.1	295.0 ± 6.5	4.3 ± 0.5	0.5
during (11.01.2022)	3.7 ± 0.7	194.2 ± 5.3	0.1 ± 0.1	330.0 ± 0.0	8.5 ± 2.5	0.2
during (10.02.2022)	3.3 ± 1.5	254.3 ± 28.4	0.1 ± 0.0	319.5 ± 28.5	6.0 ± 1.3	0.5
one month after (10.03.2022)	4.0 ± 1.2	168.5 ± 7.2	0.1 ± 0.0	347.7 ± 7.5	5.3 ± 0.5	0.1
three months after (16.05.2022)	< 1 kts	43.5 ± 19.1	< 0.1 m	-	-	0.0
six months after (11.08.2022)	< 1 kts	19.7 ± 6.3	< 0.1 m	-	-	0.0
one year after (24.11.2022)	2.0 ± 0.0	191.7 ± 5.0	0.1 ± 0.0	50.8 ± 10.1	4.8 ± 0.4	0.2

Supplementary Table S3 Content of organic particles of all total suspended sediments (TSS) in %.

time	**organic content of TSS / %**
before (14.10.2021)	31.571 ± 1.949
during (25.11.2021)	34.614 ± 11.234
during (11.01.2022)	25.842 ± 5.642
during (10.02.2022)	33.948 ± 5.714
one month after (10.03.2022)	15.302 ± 3.130
three months after (16.05.2022)	32.428 ± 6.270
six months after (11.08.2022)	14.981 ± 2.543
one year after (24.11.2022)	12.018 ± 3.371

Supplementary Table S4 The rainfall data (in mm) at the sediment sampling days and during the nourishment. Shown are mean values ± standard deviation of the daily rainfall for the month of the sampling.

time	**rainfall / mm**
before (august 2021)	3.2 ± 5.6
during (november 2021)	2.4 ± 5.3
during (january 2021)	1.1 ± 1.8
during (february 2021)	3.0 ± 4.1
one month after (march 2022)	0.0 ± 0.1
three months after (may 2022)	1.6 ± 2.8
six months after (august 2022)	0.6 ± 1.3
one year after (may 2023)	0.2 ± 0.9

Declaration of own contribution to the publications and manuscripts

Publication I:

The manuscript was published in 2023 in the journal *Marine Pollution Bulletin*. As I was the sole author of this work, no declaration of contributions to the publication is necessary.

Publication II:

The manuscript was published in 2024 in the journal *Coasts*. My work was the experimental design, sample collection and analysis. Determination of the lichen species was done in collaboration with Dr. Ulf Schiefelbein. Further, I conducted the statistical and graphical analysis of the gained data and wrote the first draft of the manuscript. I was responsible to the revision of the draft and to the responses to the reviewers during the submission process.

Publication III:

The manuscript was published in 2025 in the journal *Aquatic Botany*. I was involved in the experimental design, sample collection and analysis. Determination of sediment characteristics (grain size, sorting degree, water and organic content) was done in collaboration with Nina Feußner, as well as the floristic assessment of both terrestrial and aquatic species and the conceptual sketch of the sampling. The statistical and graphical analysis of the sediment characteristics was done in collaboration with Dr. Anne Herbst. I conducted the statistical and graphical analysis of the floristic data and wrote the first draft of the results and the discussion section of the manuscript and further edited the complete draft. I was responsible to the revision of the draft and to the responses to the reviewers during the submission process.

Publication IV:

The manuscript will be submitted in 2025. If the publication is rejected, the manuscript will be edited until it is ready for publication. I was responsible for the experimental design, sample collection and analysis. I conducted the statistical and graphical analysis of the data and wrote the first draft of the manuscript and further edit the complete draft.

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Declaration of Authorship / Selbstständigkeitserklärung

I, Daniela K. Glück, hereby declare that I have written this thesis independently and without outside help. I have not used any aids or sources other than those specified by me and I have labelled the passages taken from the works used as such.

Ich, Daniela K. Glück, versichere hiermit an Eides statt, dass ich die vorliegende Arbeit selbstständig angefertigt und ohne fremde Hilfe verfasst habe. Dazu habe ich keine außer den von mir angegebenen Hilfsmitteln und Quellen verwendet und die den benutzten Werken inhaltlich und wörtlich entnommenen Stellen habe ich als solche kenntlich gemacht.

Rostock, 12.09.2025 Daniela K. Glück

Curriculum Vitae

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Education

2021 – 2026	PhD Student, Aquatic Ecology, University of Rostock
2018 – 2020	Master of Science Marine Biology, University of Rostock
2015 – 2018	Bachelor of Science Biology, Albert-Ludwigs-University Freiburg i. Br.
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Further Training

2021	European Scientific Diver

Publications (peer review)

Daniela Glueck, Kira Preusch (2025) Sand nourishments do not foster diaspore accumulation on exposed sandy coasts at the German Baltic Sea coast. Rostocker Meeresbiologische Beiträge, 34: 44-52.

Daniela Glueck, Nina Feußner, Anne Herbst, Hendrik Schubert (2025) Ecological consequences of breakwater and revetment structures on the Baltic Sea Coast in Germany. Aquatic Botany, 198:103864. https:// doi: 10.1016/j.aquabot. 2024.103864

Daniela Glueck, Ulf Schiefelbein, Hendrik Schubert (2024) Ecological Impacts of Coastal Protection on the Vegetation of Sandy Coasts at the German Baltic Sea Coast. Coasts, 4(2):437-453. https://doi.org/10.3390/coasts4020022

Daniela Glueck (2023) Comparison of high turbidity events: Sand nourishments and storm events on sandy beaches at the Baltic Sea, Germany. Marine Pollution Bulletin, Volume 194, Part A, 115389, ISSN 0025-326X. https://doi.org/ 10.1016/j.marpolbul.2023.115389.

Scientific presentations

Baltic Sea Science Congress (Sopot, Polen): Presentation “From Waste to Resource: Unlocking the Role of Beach Wrack in Supporting Dune Stability and Coastal Habitat Health“ – awarded with “Award for Oral Presentation” (2025).

European Climate Change Adaptation conference (Dublin, Irland): Presentation “How sand nourishments can influence the ecology of coastal ecosystems: A case study” und moderation “Baltic Sea Session” (2023).

European Geoscience Union (Vienna, Austria): Poster “How much nature is in nature-based coastal management?” (2023).