SEAGRASS UNDER STRESS - A MEASUREMENT AND TESTING DESIGN FOR THE ASSESSMENT OF ENVIRONMENTAL FACTORS IN THE INTERTIDAL ZONE OF THE LOWER SAXONY WADDEN SEA

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With 7 figures
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Summary: Seagrass meadows are a complex habitat and currently under threat, mainly by anthropogenic impacts, like coastal development and eutrophication, but also by extreme weather events, like heat waves and rising marine temperatures due to climate change. The populations of *Zostera noltii* along the Lower Saxony North Sea coast have significantly declined in recent years, necessitating urgent and intensive investigations to identify the causes in order to take necessary actions. Many studies on seagrass meadows are conducted through direct field investigations. However, these studies have drawbacks, as they can only provide a fragmented picture of living conditions, environmental influences, and changes within a complex ecosystem over time. This is especially true in the intertidal Wadden Sea, where access is limited to a few hours per day. Here, automated measuring instruments that collect data consistently over a long period offer a promising alternative, with the potential to significantly enhance data collection and our understanding of seagrass ecosystems. Here, we present the possible application and advantages of a measurement system for investigating key ecological parameters in intertidal seagrass meadows, including a new expandable measurement station equipped with a multi-parameter probe, current meters, and light sensors. In combination, these devices measure the environmental conditions at low and high tide to show a comprehensive picture of the growing conditions of *Z. noltii*. We discuss data processing, challenges in application, potential for expansion, and advantages, while also presenting example data. Unlike existing measurement devices, our developed measurement station has the advantage of expandability, accommodating more sensitive water-measuring devices, as well as a large battery capacity. Live data collection via a 3G network is also integrated and can be enhanced by mounting additional antennas. The current meters we use provide long-term, high-resolution current data from the intertidal seagrass meadows, leading to an understanding of the possible mechanical stressors *Z. noltii* is exposed to. We also applied several filters to the light and temperature data collected by low-cost sensors to extrapolate the attenuation at the seagrass meadows. When used correctly, automated measurement systems have great potential to provide high-resolution data on environmental conditions in *Z. noltii* meadows, enabling early detection of emerging stressors and facilitating the identification and evaluation of suitable sites for conservation or restoration.

Keywords: Seagrass beds, *Zostera noltii*, Wadden Sea, currents, attenuation, automated measurements

1 Introduction

Seagrass occurs in all continents' coastal areas except Antarctica (Short et al. 2007, Mtwana Nordlund et al. 2016). As a key ecosystem, seagrass meadows fulfil essential functions for the preservation of the ecosystem in various ways. Additionally, seagrass meadows significantly contribute to biodiversity by serving as a refuge for various organisms in the Wadden Sea (Bertelli & Unsworth 2014). As primary producers, they contribute to the nutrient cycle (McGlathery et al. 2007). Through their influence on hydrodynamic processes, dense root systems and rhizomes, seagrass meadows promote sedimentation processes and thus contribute to sediment stabilization (Orth et al. 2006, de Boer 2007). They also provide an important food source for herbivore birds (Ganter 2000, Nacken & Reise 2000, Zoffoli et al. 2022). Furthermore, they function as marine carbon sinks (Duarte et al. 2005, Fourqurean et al. 2012).

Nonetheless, seagrass meadows are one of the most threatened ecosystems on Earth. The global loss rate in the 1940s was 0.9% per year and, up until the end of the 20th century, went up to 7% per year (Waycott et al. 2009). In Europe, the loss from 1869 to 2016 is assessed to be one third of the original seagrass area (de los Santos et al. 2019), even though there are also areas in Europe where seagrass recovered or stabilized (Barillé et al. 2010, Dolch et al. 2013). Along the Lower Saxony Wadden Sea coast, no subtidal seagrass populations have been recorded since the mid-20th century due to a global infection with the marine net slime mold *Labyrinthula zoste-*

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rae (Sullivan et al. 2018). The seagrass population along Germany's Lower Saxony North Sea coast has experienced strong fluctuations over the past decades. After a significant decline between 1970 and 1990 due to eutrophication, the populations began to recover from 2000 onwards (Adolph 2010). Since 2014, seagrass populations in Lower Saxony have been in sharp decline again. During the last large-scale mapping in 2019, the total coverage was only 8.6 km² from the previous 37.57 km² in 2013 (Küfog GmbH & Steuwer 2020). In the intertidal zone (as of 2019), *Zostera noltii* is predominantly found, while isolated populations of *Zostera marina* still exist in some areas (Küfog GmbH & Steuwer 2020). There are various known threats to seagrasses (Philippart et al. 2020). Sediment extractions and dredging can impact the plants by burial or light reduction in the water column (Erftemeijer & Robin Lewis 2006). Turbidity reduces seed production, seedling survival, and seagrass rhizomes (Cabaço et al. 2008). Eutrophication can limit light availability for submerged vegetation by driving phytoplankton and epiphyte growth, impacting the plants similarly to increased turbidity. Furthermore, eutrophication can impact plant survival directly due to ammonium toxicity, leading to decreased shoot rates, and rhizome and root elongation (Van Katwijk et al. 1997, Brun et al. 2002, Philippart et al. 2020). Furthermore, weather extremes like heat waves and storms have a negative impact on seagrass populations (Massa et al. 2009, Gera et al. 2014, Hernán et al. 2017). Although many parameters that can be harmful to *Z. noltii* are known, it is challenging to identify and determine a specific factor that directly contributes to the current decline of seagrasses along the Lower Saxony North Sea coast or that may have had a negative impact on the population since the late 2010s. Increased current velocities represent a general mechanical stress factor for *Z. noltii* (Schanz & Asmus 2003, Peralta et al. 2006, Widdows et al. 2008, Hansen & Reidenbach 2012). An increase in current velocity leads to a reduction in leaf area and, consequently, a decrease in photosynthetic capacity (La Nafie et al. 2012). Current velocity also influences the physiology of *Z. noltii.* The plant develops longer roots, among other adaptations, to anchor itself more effectively in the sediment (Schanz et al. 2003, Peralta et al. 2006). Furthermore, increased current velocities pose a problem for grazers, which help remove epiphytic growth from the leaves (Schanz et al. 2002). The symmetry of tidal currents during ebb and flood can be relevant for the vitality and expansion of seagrass meadows due to its impact on current-induced sedimentation processes. An asymmetry in current velocities at an intertidal, flood-dominated site promotes sediment accumulation (Scully & Friedrichs 2003, Kostaschuk & Best 2005, Scully & Friedrichs 2007, Chen et al. 2010, Sommerfield & Wong 2011, Livsey et al. 2020). In contrast, an ebb-dominated asymmetry favours sediment erosion, which also depends on the duration and intensity of the ebb tide (Dronkers 1986, Ralston et al. 2013, Jiang et al. 2020, Feng & Feng 2021, Jacob & Stanev 2021).

Light is the primary influencing factor on the growth of seagrass meadows (Zieman & Wetzel 1980, Hemminga & Duarte 2000, Peralta et al. 2002, Pergent-Martinì et al. 2005). *Z. noltii* has a significantly lower light requirement than other seagrass species (Erftemeijer et al. 2006) and does not exhibit a negative growth trend in laboratory experiments when exposed to only 2% (0.8 mol photons m^{-2} day^{-1} in an experimental setting) of surface radiation (Peralta et al. 2002, Erftemeijer et al. 2006). Light conditions below the energy requirements of *Z. noltii* lead to increased plant mortality. In experiments investigating the vitality of seagrass plants under phases of increased turbidity, larger seagrass species with higher storage capacity were found to be less sensitive to turbidity increases than smaller species. However, smaller species could recover faster than larger ones once the original light conditions were restored (Erftemeijer et al. 2006).

The ability of a plant to adapt morphologically to increased turbidity, such as by extending its leaves, can provide an advantage when light conditions are suboptimal, as the leaves remain closer to the water surface in low-current conditions (Vermaat et al. 1997). Additionally, seasonal variations exist in the photosynthetic activity of seagrass plants, such as *Z. noltii* populations along the North Sea coast. This means increased turbidity outside the growth period is likely less harmful to the plants than during the active growth period (Vermaat et al. 1997). Because seagrasses are sensitive to environmental changes (Dennison et al. 1993, Orth et al. 2006), *Z. noltii* serves as an indicator species for local water quality. Based on the European Water Framework Directive (EU-WFD), it is used as an indicator for the condition of transitional and coastal waters along the North Sea coast due to its sensitivity to eutrophication (European Parliament and Council 2000). To investigate the causes of this decline in *Z. noltii* populations in Lower Saxony, the SeeUS "Seagrass Under Stress" project was launched in 2021 as a cooperative initiative between the Lower Saxony State

Agency for Water Management, Coastal and Nature Conservation (NLWKN) and the Geoecology Research Group at the Institute for Chemistry and Biology of the Marine Environment (ICBM) at Carl von Ossietzky University Oldenburg. It turned out that the root cause analysis of this decline of *Z. noltii* in Lower Saxony is challenging. The temporal and spatial variability in intertidal research areas demands a flexible setup and resistant equipment; fieldwork in intertidal zones also comes with logistical challenges due to time restrictions between tidal cycles and accessibility. Since various factors can impact seagrass meadows, simultaneous measurements of several parameters are necessary for causal research of the seagrass decline. In-person measurements in intertidal seagrass meadows have time limitations, limiting the temporal and/or spatial resolution of the data.

To overcome the logistical and methodological challenges of environmental monitoring in intertidal seagrass ecosystems, we developed a modular and field-adapted measurement system. This system combines three complementary components: a custom-built, remotely accessible, and vastly expandable measurement station for automated, long-term data acquisition; low-cost light sensors arranged vertically to calculate light attenuation; and compact current meters for quantifying hydrodynamic stress over time. The station is designed for flexible deployment under harsh tidal conditions. It is corrosion-resistant and stable against current conditions in the seagrass meadows, while also being expandable by providing great battery capacity and space in and on the station, enabling real-time data transmission for responsive field management. The use of vertically stacked light sensors enables site-specific insights into light availability and attenuation within the water column, which is crucial for assessing light limitation as a stressor on *Z. noltii*. In parallel, continuous current velocity measurements provide essential data on mechanical stress in seagrass habitats. This integrative, low-maintenance monitoring approach closes a key methodological gap for intertidal research and enables high-resolution, multi-parameter measurements in locations that are otherwise difficult to access. It supports adaptive, data-driven decision-making and benefits coastal managers, restoration projects, and researchers aiming to understand and mitigate the drivers of seagrass decline.

The following will provide an insight into examples of our remote measuring techniques for water chemistry, current velocity, and light attenuation. The background of the analysed parameters and the technical setup will be described in detail, followed by exemplary data and an overview of a future advanced sensor setup presented.

2 Sample sites

For the study, a seagrass meadow on a back-barrier tidal flat on the mainland shore opposite the island of Norderney and a seagrass meadow on the eastern side of Jade Bay were selected. Furthermore, light sensors were deployed on the shoreline of the island of Mellum as a proof-of-concept to assess the general applicability of light sensors for calculating light attenuation in the water column, as described in Section 3.3 (Fig. 1).

The sites were chosen because they differ significantly in their structural characteristics as back-barrier and bay tidal flats and in the intensity of their seagrass loss. The seagrass area on the Lütetsburger Plate (from now on referred to as mainland shore site) is located in the protected back-barrier tidal flat

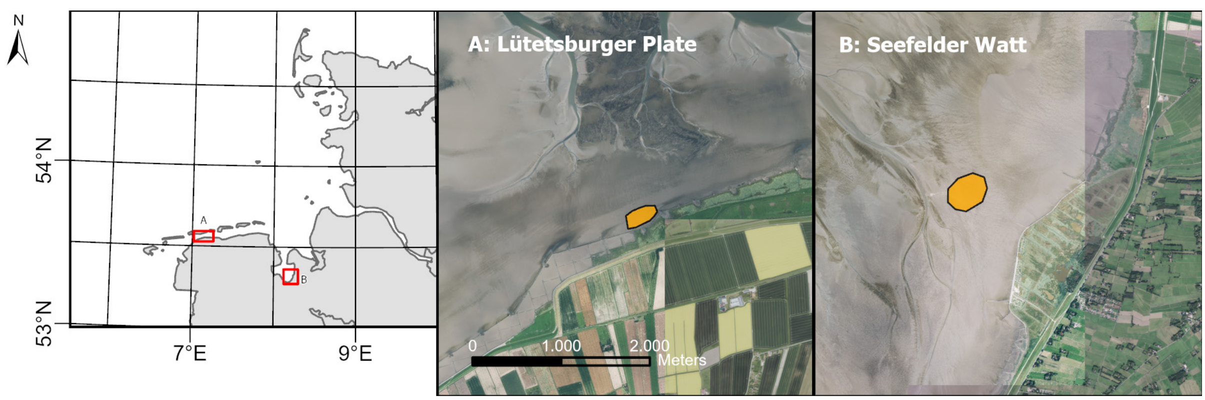

Fig. 1: Sample sites on the coast of the German North Sea: Lütetsburger Plate, a back-barrier tidal flat of the island of Norderney, and Seefelder Watt, a tidal flat on the eastern side of Jade Bay (orange polygon). The blue marker points to the position of the light sensors on Mellum. Source: GeoBasis-DE/LGLN 2025).

of the island of Norderney (Böse et al. 2022). The seagrass populations here have been in decline for some time. While the seagrass meadows covered approximately 0.2 km² between 2003 and 2013, they had shrunk to 0.12 km² by 2019 (Küfog GmbH & Steuwer 2020). The seagrass meadow in Seefelder Watt (from now on referred to as tidal bay site) is located in Jade Bay, a sheltered bay tidal flat with lower current velocities than the open North Sea (Reineck 1962, Schückel et al. 2013). Over the past ten years, this area has experienced the most significant decline in seagrass coverage. Of the 8 to 9 km² of seagrass recorded in 2008, only 1 km² remained by 2019 (Küfog GmbH & Steuwer 2020). The island of Mellum is located between the Jade and Weser estuaries. Although no seagrass beds were investigated there in this study, Mellum was selected as an additional site to test the light sensors for both logistical reasons and its highly dynamic geomorphological setting. Wadden Sea islands such as Mellum undergo continuous erosion and sedimentation, causing frequent changes in surface elevation and shoreline structure (Kleyer et al. 2014). These processes can lead to fluctuating light conditions in the near-shore water column, making Mellum a suitable reference site for evaluating sensor performance under variable environmental conditions.

3 Measurement systems and exemplary datasets

Monitoring environmental drivers in intertidal seagrass ecosystems presents unique methodological challenges. Access to sites is restricted to short windows during low tide or requires access by boat, while many relevant abiotic parameters can only be recorded during submersion. Variables such as light availability and temperature can be measured throughout the tidal cycle, but would benefit from a flexible, low-cost array of measurement spots to determine the conditions on the outer borders of seagrass meadows. Since light intensity alone is insufficient information, it is necessary to calculate attenuation using the light data that these sensors can provide. Furthermore, a long-term overview of the current velocity speeds endured by *Z. noltii*, as measured by current meters, is necessary to obtain data on extreme events and tidal speeds that would be difficult to obtain otherwise. As a result, obtaining a continuous and representative dataset demands a combination of complementary sensor types.

To be able to react to sudden environmental changes, such as sudden increases in turbidity but also fouling events, remote access to live data to evaluate sensor performance and to adapt monitoring strategies during the deployment period is needed. At the same time, the logistical constraints of working in tidal flats require measurement systems to be lightweight, deployable by a single person, and minimally invasive to the habitat. At the same time, measurement systems should remain structurally flexible, allowing for the addition of further instruments without compromising water resistance or system stability.

3.1 Multi-parameter measurement station

To meet the methodological requirements for automated long-term measurements in intertidal seagrass meadows, existing measurement systems are insufficient, especially in terms of expandability. A custom-built measurement station was developed to collect abiotic water column data during tidal submersion. The system was designed to be watertight, robust against hydrodynamic stress, operable over several weeks without maintenance, and deployable by a single person under typical field conditions in intertidal zones. The station consists of a self-designed tripod frame that stabilizes a vertical tube, sealed at the top and open at the bottom, which houses the internal components. It is fixed to the sediment using three 1.5-m aluminium rods, providing both structural stability and corrosion resistance. This construction ensures that the electronics remain dry while submerged and creates a stable platform for integrating additional sensors. Its low weight and modular design allow for transport and installation by a single person, minimizing site disturbance during deployment (Fig. 2).

The central unit contains a rechargeable battery, which can be easily exchanged during maintenance, a data converter (SDI-12), and a Remote Telemetry Unit (RTU), which processes the data received from the measurement equipment. Sensor measurements are collected by a multi-parameter probe (Aquaread AP-6000), which is placed approximately 10 m away on a separate frame to avoid flow interference caused by the station itself. The probe features sensors for pH, conductivity, salinity, turbidity, temperature, depth, and alkalinity. It offers ports for additional sensors, such as chlorophyll a, ammonium, nitrate, or CDOM, allowing the system to be adapted to various research objectives. Measurements are con-

Fig. 2: Measurement station on the mainland shore site. In the foreground, the station's core contains the telemetry, power supply, and data-processing units; in the background, the probe collects the data, which is further processed in the central station.

ducted at 30-min intervals. Data is transmitted automatically via the 3G mobile network to a server hosted by Metasphere (Metasphere Ltd, UK) for remote access. The system supports real-time data monitoring, allowing early identification of anomalies such as unusual environmental events or sensor fouling, and enables targeted field responses where necessary. Signal strength can be enhanced with external antennas to improve data reliability in remote locations. This station design offers a flexible and practical solution for continuous monitoring in tide-controlled environments. As an exemplary dataset, in August 2023, lower salinity levels and a slightly higher pH value were observed in the tidal bay site. Temperature trends were comparable at both stations. The station in the tidal bay site was submerged deeper at high tide and exhibited significantly higher turbidity than the station on the mainland shore site.

In the graph below (Fig. 3), all data points were removed where salinity was <10 ppt and pH was <5 or >10. This ensures that only measurements are considered when the station was underwater. Average, maximum, and minimum values were calculated for each day. The line represents the daily average value, while the shaded areas indicate the daily maximum and minimum values.

The temperature shows the same progress in the tidal bay site and the mainland shore site during August 2023. The mean temperature at around 18 °C is increased compared to the long-term mean surface temperature during summer in the North Sea of around 15 °C (Boersma et al. 2016). This may be explained by the relatively low water depth and temperatures in August. The turbidity at both sample sites is very high with an average of 150 NTU (refers to Nephelometric Turbidity Unit; a unit for the measurement of turbidity based on absorption of light and scattering in a liquid) at the mainland shore site and 300 NTU at the tidal bay site, often exceeding 1000 NTU For comparison, the river Thames had a mean turbidity of 150.78 ± 8.36 NTU from 2014 to 2020 (Firth et al. 2024). A notable feature is the increase in pH towards the end of the month in the tidal bay site. This is not a natural increase, as it is too extreme for North Sea water in this environment, but rather an indicator that the station was colonized by barnacles and required cleaning. Hence, one limitation of probing equipment in tidal zones is high-frequency maintenance to avoid fouling. In 2023, high temperatures strongly promoted the growth of barnacles (Fig. 4), leading to frequent data interruptions until the probe was cleaned and recalibrated in the field. Since other months in the measurement series also frequently showed interruptions due to barnacle growth, August 2023 is presented here. The test datasets already show great potential and could be collected online daily.

Generally, cross-site comparisons of turbidity values should be interpreted with caution. Differences in particle composition and size between different locations may result in distinct optical effects for the same turbidity value. Furthermore, sensor design may influence the measurement. For the interpretation of turbidity data, it is essential to consider the limitations of turbidity as a unit for measuring light availability. Turbidity data reflect scattering, but not absorption. While turbidity is a valuable indicator for relative comparisons, it does not fully capture total light attenuation and must be used solely as a proxy

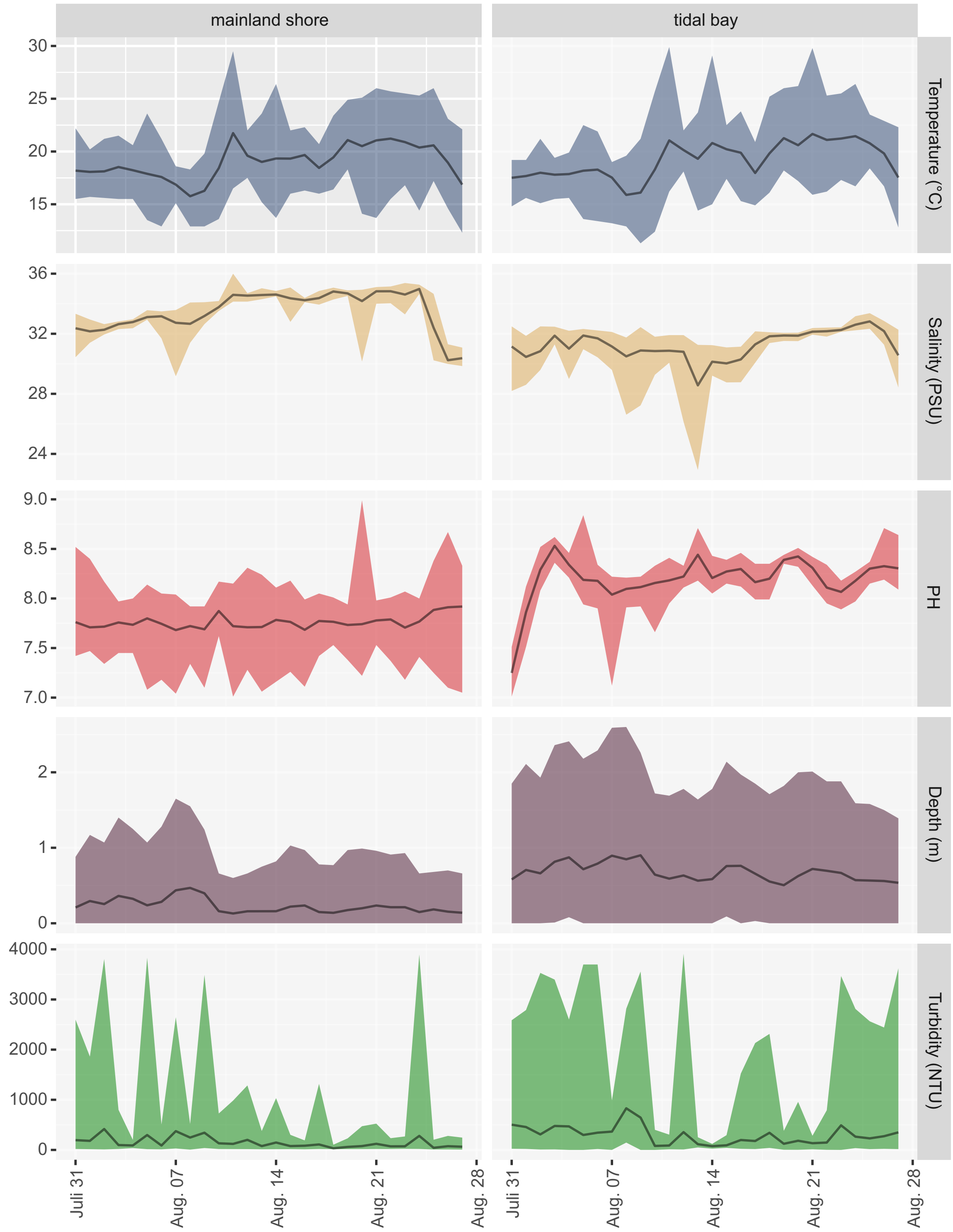

Fig. 3: Measurements of temperature, salinity, pH value, depth, and turbidity over August 2023 at the locations tidal bay and mainland shore

Fig. 4: Infestation with barnacles at the measurement station. Left: Heavy infestation on the probe. Center: Infestation on the sensors inside the protective casing. Right: Sensor after cleaning.

for water clarity and light availability (Grünler & Sellhorn 2018, Fettweis et al. 2019). Turbidity in this study is used with caution for comparison with other turbidity data.

After intense fouling events, calibration of every sensor is necessary. An additional exchange multi-parameter probe would make this process more efficient since the probe can be cleaned with fresh water overnight, which is less wearing on the probe than scrubbing in the field. The multi-parameter measurement stations already deliver essential information about the water chemistry surrounding the seagrass meadows. Other than additional sensors that can be installed on the multi-parameter probe, external sensors that can be deployed at some distance around the station and collect data on physical and biological parameters are a valuable addition to the measurement setup for researching seagrass growing conditions.

3.2 Current meters

So far, there are only a few published datasets on current velocities in *Z. noltii* meadows. These datasets were measured using a handheld device at the Schleswig-Holstein North Sea shore near Sylt over one vegetation period at twelve time points under calm weather conditions (Schanz et al. 2003). In areas with sparse vegetation, current velocities ranged between 0.2 and 0.3 m s^{-1}, whereas in less exposed, more vital seagrass meadows, lower current velocities between 0.04 and 0.2 m s^{-1} were recorded (Schanz et al. 2003).

As part of the SeeUS project, current meters (Lowell Instruments TCM-1 without ballast) were installed in the seagrass meadows at the mainland shore site and the tidal bay site to measure current velocities. The current sensors determine flow velocity through an inclinometer coupled with a magnetometer, which records tilt angles in the north and east. At low tide, the sensor lies flat on the seabed and gradually tilts upright as it becomes submerged. This initially results in data showing an increase in current velocity that is not present. In 2022, measurements were taken from September 6 to October 15 at five-minute intervals, and in 2023, from June 2 to August 30 at 1-min intervals. Both times were chosen due to logistical constraints. For statistical analysis, high tide times from tide predictions of the Federal Maritime and Hydrographic Agency (BSH) for 2022 and 2023 were used to select a 2-hr time window around each high tide from the current velocity data.

Due to recurring barnacle growth, measurement disturbances occurred when the current sensors could no longer float adequately. To eliminate erroneous data caused by sensor fouling, current velocities exceeding 40 cm s^{-1} were removed from the datasets. A review of the raw data showed that this threshold was only exceeded shortly before the sensors were maintained and cleaned, when significant fouling was present, or when the sensors were exposed during low tide. Based on current velocities recorded during high tides, average flow velocities were determined in 2023. The median current speed on the mainland shore site is higher than on the tidal bay site. Additionally, the mainland shore site exhibits a wider interquartile range and greater overall variability in current speeds, with values ranging from near 12 cm s^{-1} up to approximately 28 cm s^{-1}. In contrast, the tidal bay site shows lower overall current speeds, with most values falling between roughly 5 cm s^{-1} and 25 cm s^{-1} (Fig. 5).

Additionally, reversals in the northward tilt direction were used to determine the exact peak of each high tide. These time points were then used to calculate the average flood and ebb current velocities. This is possible as long as the scaling resolution is very high. Due to isotropic turbulence, these calculations should still only be used for an estimation.

3.3 Turbidity

Over the past decades, light conditions have changed, as recent studies indicate an increase in turbidity and a reduction in light availability over the last hundred years (Dupont & Aksnes 2013, Capuzzo et al. 2015, Thewes et al. 2021). A deterioration in light conditions may result from phytoplankton blooms triggered by eutrophication (Cambridge et al. 1986, Shephard et al. 1989) or from natural or anthropogenic sediment resuspension (Short & Wyllie-Echeverria 1996). Dissolved particulate and organic material significantly impact water column darkening (Harvey et al. 2019, Opdal et al. 2019).

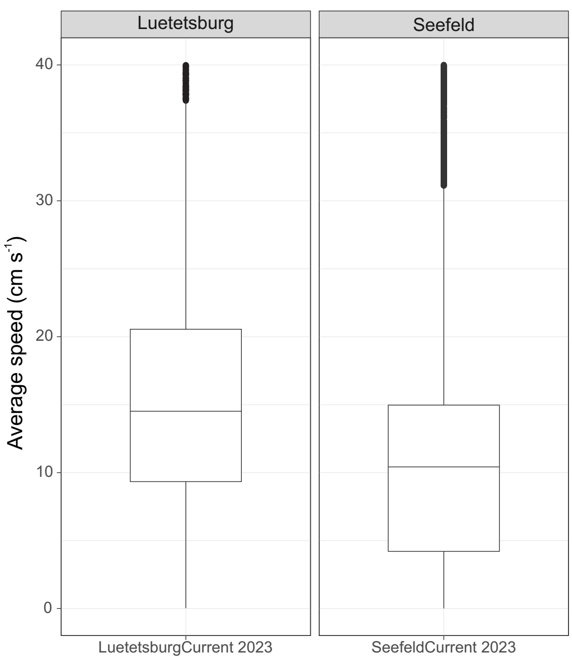

Fig. 5: Exemplary current speeds at the mainland shore site and the tidal bay site

To assess light conditions, in different locations, waterproof two-channel data loggers for temperature and light recording (ONSET HOBO Pendant temp/light UA-002-64) were installed in the tidal flats of the bay site (Seefeld) and near Mellum at the opening of Jade Bay from June 1st, 2023, (June 23rd, 2023 at Mellum) to September 30th, 2023due to logistical constraints. The loggers were placed at 20 cm and 40 cm height on a southward-oriented pole (Fig. 6) and cleaned every two weeks. The height was chosen since data from the measurement station indicated that the water column frequently reached this level at both locations. The lower logger height was chosen because it was close to the average maximum leaf height of 20 cm measured in the field, and the distance between the upper logger was selected to achieve extended coverage. It is crucial to measure the distance between the loggers at every logger station so it can be fitted to the calculations. Light intensity is measured in lux.

An attenuation coefficient can be calculated using two loggers in this configuration. This is derived from the equation for light intensity at depth z:

$$L(z) = L_0 exp\ (-k_D\, z) \tag{1}$$

where L represents light intensity, and k_D is the downward attenuation coefficient. Substituting the two depths and corresponding intensities yields:

$$k_D = \ln\left(\frac{L(z_1)}{L(z_2)}\right)\ (z_2 - z_1) \tag{2}$$

Using an approximation, irradiance can be calculated from light intensity. This is done by averaging the spectral luminance of sunlight and dividing the light intensity by this average value:

$$l = L/\Phi \tag{3}$$

Where Φ is the spectrally averaged luminance of sunlight; a typical value for atmospheric measurement devices is Φ = 126.7 lm/W. However, the actual value depends on the spectral composition of incoming light, which is influenced by cloud cover, solar position, and other factors, including seawater effects. As a result, the generated irradiance data are not directly usable or publishable. Therefore, the values measured in water are likely incorrect and probably overestimated. Consequently, the calculated values for the attenuation coefficient k_D are only qualitatively meaningful and not transferable to direct measurements of k_D, such as those obtained using profilers. However, at greater number, both in space and time, they can

Fig. 6: Light-Loggers fitted on the pole of the multiparameter measurement probe rack

help understand horizontal gradient and temporal variability of light availability. Their value thus stems from comparisons to each other. Via a statistical relation with profiler or Secchi disk data, a widely used optical method that measures water transparency (Secchi 1865, Wernand 2010), it may hypothetically be possible to relate the data derived from the light loggers used in this study to physically sound measurements. Since both profilers and Secchi disk data typically require a vessel or a platform to take measurements from, they are much harder to obtain than the logger data is. Therefore, such a relation between the two types of measurement may vastly extend our knowledge of the Wadden Sea light climate and make measurements possible and feasible, where they have so far not been.

As proposed by Lee et al. (2015), correlations with Secchi depths are theoretically possible but likely subject to significant error due to the limitations of this approach. A higher attenuation coefficient corresponds to higher turbidity. Data filters need to be applied to eliminate noise and clean the data to compare data across locations, as explained in the following. Since measurements at Mellum only began on June 23rd, the first filter set the measurement period to June 23rd, 2023, to September 25th, 2023. Subsequent filters ensure that data is only considered when both loggers at a given site are submerged, which is necessary for the method's validity, as only then both sensors are measuring within the same medium. It is assumed that in such cases the lower sensor must receive less light than the upper sensor, as water is much more turbid than air, thereby excluding all values where $k_D<0$. Additionally, values for $k_D=0$ are excluded as they are either physically impossible and therefore clearly outliers, or they are taken at low light conditions (e.g. at night).

Temperature differences greater than 1 °C indicate that the upper logger is not submerged, while the lower logger is. This could be used as a detection criterion in an algorithm to refine filtering in combination with tide-level data. A similar approach is taken with light intensity: differences exceeding 5000 lux are assumed to indicate that the lower logger is submerged while the upper logger is not. Furthermore, based on the calculated irradiance, values above 300 W/m² in water are considered unlikely for the lower logger, while for the upper logger, a threshold of 500 W/m² is set. While theoretically possible, exceeding this value likely represents an edge case where atmospheric and surface effects introduce excessive distortion. Moreover, temperatures above 25 °C in the North Sea are unrealistic and, therefore, assumed to represent air temperatures further distorted by insolation. Additionally, values where $k_D>24$/m are excluded, as they are unrealistically high and definitely recorded outside of the water based on a comparison between k_D and irradiance. After applying these filters, reliable approximated data are obtained. Although these do not represent actual turbidity and cannot be converted into Secchi depths, they allow for comparing different sites using the same measurement setup. After applying all filters, the values for k_D show the same ratio as before using the filters; however, there are slight shifts after applying the time filter (Fig. 7).

This can be explained by the fact that the quick filters only work reliably in summer, as water and air temperatures often do not differ significantly in autumn. Mellum shows a higher median turbidity than Seefeld. The tidal bay site (Seefeld) has a lower median than Mellum but exhibits greater variance. It can thus be assumed that actual median turbidity at the tidal bay site location was lower than in the Mellum tidal flats, and that turbidity fluctuated more at the tidal bay site compared to Mellum. The data is promising, but establishing specific algorithms for each location could reduce measurement errors. Alternatively, and in the long term, more cost-effec-

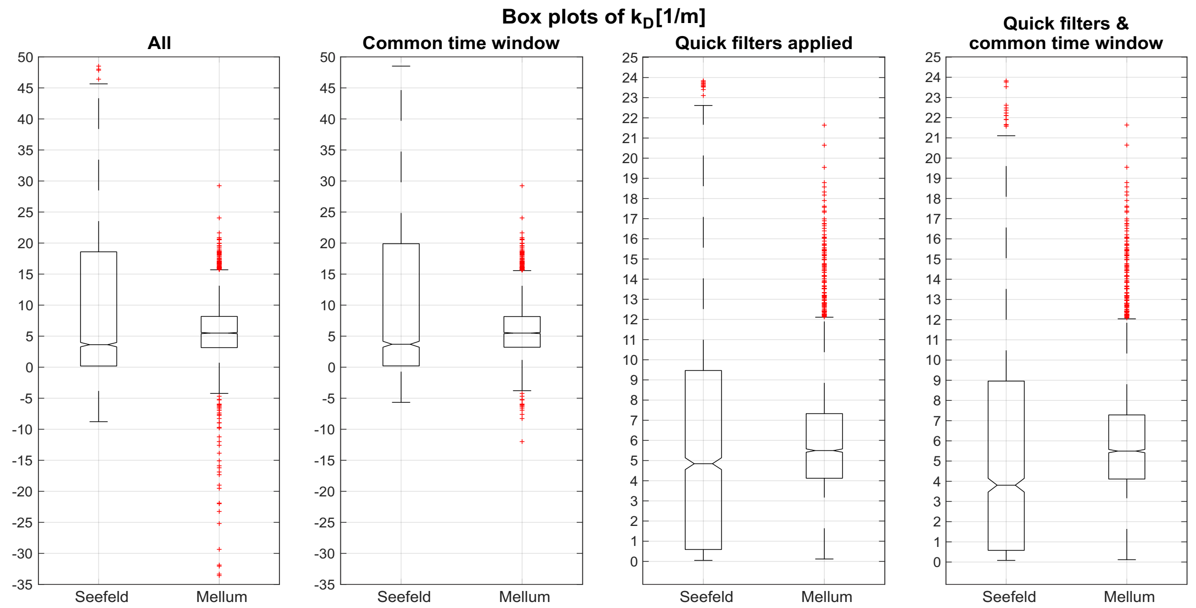

Fig. 7: Representation of the attenuation coefficient k_D for the locations Seefeld (tidal bay site) and Mellum (island in the opening of the tidal bay site). June 23rd, 2023, to September 25th, 2023. Left: 'All', all data for the respective stations, without time or other filters. Middle left: 'Common time window', only data within the time window for which all loggers have data. Middle right: 'Quick filters applied', all data, without applying the time filter, but after using the quick filters described in the text. Right: 'Quick filters & common time window', time and quick filters applied.

tive, would be measurement systems such as gauges that detect when a logger is submerged. Another obvious advantage of using light sensors to calculate attenuation is that these devices also provide live data during low tide, when they measure air temperature and light intensity.

However, to obtain precise information on radiation intensity relevant for *Z. noltii*, using sensors for photosynthetically active radiation is indispensable. For this purpose, tested sensors (PAR Sensor DEFI-L from JFE Advantech) were used in 2024, which successfully provided data on artificial islands as part of the now discontinued project "Coastal Observatory Spiekeroog (SCO)". Loggers of the same type have been used in other studies and are well-established in marine sensor technology (Long et al. 2012, Omand et al. 2021).

4 Conclusion

In response to the ongoing and concerning decline of *Z. noltii* populations along the Lower Saxony Wadden Sea coast, this study has presented a modular, automated measurement design that supports high-resolution, in-situ environmental monitoring during high tide. As emphasized in the introduction, understanding the complex and interrelated ecological factors that affect seagrass meadows, particularly under the constraints of the intertidal zone, requires both innovative methodology and consistency in data acquisition. Data collected using multi-parameter measurement stations, which send data remotely and have the capacity for even more devices, current meters, and light attenuation setups, in combination with on-site measurements of plant physiology and pore-water chemistry, will provide a comprehensive overview of the living conditions of seagrass meadows at the sample sites. Through the combination of turbidity measurements, current velocity, and in-field measurements of sedimentation rates and sediment pore-water chemistry, the growth conditions within the seagrass meadows can be derived, and estimates for future development can be extrapolated. The impact of these conditions on the plants can be determined by correlating them with plant physiology data. Automated monitoring of these parameters can lead to an early warning system for seagrass meadows, where rising temperatures or sudden spikes in turbidity indicate emerging threats to these ecosystems. Furthermore, automated measurement devices such as the setup used in this study may help identify suitable locations for potential restoration, provided that the measured environmental parameters at a candidate site are comparable to those observed at long-term stable seagrass meadows.

Compared to in-field measurements by scientists, continuous measurements by a comprehensive measurement system provide an uninterrupted data series during high tide, but also by measuring the light conditions during low tide, allowing for the collection of data during extreme weather events and under night conditions, thereby enabling the collection of all necessary clues for understanding the living conditions of seagrass. Ultimately, this approach lays the groundwork for a more comprehensive understanding of seagrass decline, enabling researchers, conservationists, and policymakers to identify causative factors more precisely and develop timely and targeted mitigation strategies.

The platform of the multi-parameter measurement stations can accommodate further measurement devices since both the hardware setup and the large battery capacity are expandable. The deployment of automatic self-closing Niskin bottles would be a promising addition to the setup since it provides samples of the water body during high tide. Furthermore, integrating chlorophyll and ammonium sensors would allow turbidity to be linked to either particulate inorganic matter or eutrophication-driven phytoplankton blooms. For the current meter, additional current meters arranged in a transect may help to identify the limits of possible seagrass growth as set by water current speed. Furthermore, custom-made current meters using single-axis equilibrium acceleration sensors are compatible and as effective as the current meters used in our set-up, as long as they are adequately calibrated (Balke et al. 2021).

The light measurements need to be extended by sensors for photosynthetic active radiation. Furthermore, turbidity data needs to be measured with more sensors and correlated with Secchi depth. These mini-stations, containing two light loggers and a PAR sensor, can be implemented along a transect from the seagrass meadows to the open North Sea to monitor possible turbidity developments.

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