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Erosion resistance of vegetation-covered soils: Impact of different grazing conditions in salt marshes and analysis of soil-vegetation interactions by the novel DiCoastar method

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ABSTRACT

The analysis of soil-vegetation interactions in erosion processes along coastlines requires accurate information about various factors influencing the upper soil layer. Yet, some of these parameters were previously determined by simplified, often hand held devices, and these were often biased by the skill and experience of the operator. This study thus investigates the erosion resistance of salt marsh soils influenced by grazing conditions for providing crucial findings for policy making and land management decisions; to that end, we present and use a novel shear resistance measuring device. This measuring device, called *DiCoastar*, was developed with a controllable step-motor and now allows us for the first time the determination of time histories of shear resistance by repeatable in-situ measurements, gaining information about the interaction between soil and root systems. A field study was conducted in salt marshes at Cäciliengroden and at Sönke-Nissen-Koog, both foreland salt marshes at the German North Sea coast. The two sites had been chosen due to their difference in grazing intensities, featuring semi-natural/ungrazed, moderately grazed and intensively grazed salt marshes. This was to enable the investigation of influences on soil shear strength and vegetation cover. Measurements of shear resistance were conducted with the *DiCoastar* in the chosen sites in the vicinity of the dike toes; it is found that the new device now provides consistent and repeatable measurements, irrespective of the operator, and only based on the pre-set control parameters. Results of the field study demonstrate that a marked increase of shear strength is only found in sites with high intensity grazing, but this is accompanied by a strong reduction in the vegetation cover and plant diversity, especially with regard to the vertical density distribution of the vegetation cover. As the reduction in vegetation cover leads to reduced wave attenuation over salt marshes and increased flow velocities, an increased shear stress on the soil surface, which potentially exceeds the increased shear strength, is expected. Based on this, the results obtained lead to the assumption that an increase in the erosion potential of these foreland marshes by high grazing pressure is more likely as well as a reduction in dike stability.

1. Introduction

Global soil erosion is long recognized (Ayres, 1937a; Ayres, 1937b) and easily one of the most important process, shaping the worlds continents from regional scale catchment areas, along river valleys traversing agricultural farm land, discharging into the oceans lined by erosion prone coastlines (Water conservation, soil erosion and land use, 1949; Smith, 1963). Annually an estimated 35 Pg to 43 Pg (1 Petagram equals 1 billion tonnes) of soil is eroded and washed into the oceans, where it settles; at this stage it is permanently lost from the land based nutrient cycle (Borrelli et al., 2017; Borrelli et al., 2020).

Loss of soil causes diminished crop and plant fertility, as the productive and nutrient rich layer containing nitrogen, carbon and especially scarce phosphorous, the base component of bones and a main plant nutrient, is eroded (Alewell et al., 2020). Current erosion rates average 1 mm ha^{-1} yr^{-1} globally and exceed natural soil formation processes by a factor of 1 to 2 (Montgomery, 2007). It is widely acknowledged, that anthropogenic land cover changes induced by

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deforestation, livestock cultivation and intense conventional farming exacerbate soil erosion rates (Montgomery, 2007; Low, 1978). A lot of research was dedicated to soil erosion, from establishing soil conservation services (Ayres, 1937b; Smith, 1963) to mitigate erosion, to afforestation programs and refraining from farming erosion prone geographic locations (Water conservation, soil erosion and land use, 1949) to changes in national farming practices (Borrelli et al., 2017; FAO and ITPS, 2015), which were recently shown to impact country based erosion rates by 1.4 t ha^{-1} yr^{-1} on average (Wuepper et al., 2020).

Naturally, resistance of the surface soil layer against alluvial or fluvial erosion is of major importance for conserving, stabilizing and regenerating ecosystems and landscapes. Consequently, the reliable assessment and quantification of soil erosion resistance constitutes a crucial first step towards developing sustainable and optimal land management solutions.

Apart from water content and ambient humidity being influential factors for eolian and alluvial erosion (Ravi et al., 2006; Wiggs et al., 2004), vegetation coverage is a decisive factor in controlling soil erosion, shielding soil from direct sediment entrainment and stabilizing the covered soil matrix through their systems of roots and rhizomes (Dugan et al., 2011; Zobeck et al., 2013).

Within coastal areas, the focus area of this work, vegetation is assumed to play a special role, as it not only covers and protects soil from general erosion processes, but also dissipates impeding wave and tidal current forces, reducing the overall loads, induced shear stresses and in turn erosion (Dugan et al., 2011; Bouma et al., 2007; Chen et al., 2011; Ford et al., 2016; Ghisalberti and Nepf, 2006; Li and Yan, 2007; Nepf and Vivoni, 2000).

Salt marshes, in particular, have been shown to bear great wave and current dissipation capabilities (Maza et al., 2020; Möller et al., 2014; Peruzzo et al., 2018). Salt marshes retain suspended sediments and accumulate soil instead of losing it to the ocean, rendering them a vital addition to coastal ecosystems. As a result, the preservation of salt marshes is increasingly assumed as a sustainable strategy to protect the coastlines from erosion caused by climate change and the associated sea level rise (Adnitt et al., 2007; Brooks et al., 2021; Feagin et al., 2009; Baptist et al., 2021). Thus, these systems need to be better understood and integrated into standardized coastal protection guidelines instead of replacing them with conventional dams and dikes, which often lack biodiversity and do not provide equal ecosystem services (Barbier, 2019; Costanza et al., 1997; McKinley et al., 2018). Studies on the erosion resistance of salt marshes highlighted the importance of sediment supply, sea level change as well as human interventions (Brooks et al., 2021; Alldred et al., 2017; Andersen et al., 2011; Davidson et al., 2017). With regard to the implementation of grazing management at salt marshes, an increased soil shear resistance due to soil compaction by trampling has led to the assumption that grazing enhances the erosion stability of salt marshes (Brooks et al., 2021; Stock et al., 1998), but influences on vegetation cover or biostabilization interactions between soil and root systems are disregarded. The plant diversity of salt marshes decreases as well as the vegetation cover with regard to density and canopy height due to grazing management (Bouma et al., 2007; Chen et al., 2011; Ford et al., 2016; Li and Yan, 2007; Nepf and Vivoni, 2000; Bockelmann and Neuhaus, 1999). Moreover, soil erosion rates decrease with an increase in plant species richness (Ford et al., 2016). However, grazing of salt marshes is also often associated with an increase in biodiversity due to enhanced opportunities for seedling establishment (Bakker, 1985; Bredemeier et al., 1999).

Nevertheless, acquiring reliable, consistent and reproducible measurements of soil shear resistance, given the demanding field conditions as present in coastal salt marsh regions, remains difficult (Brooks et al., 2021; Ghosh, 2013; Jafari et al., 2019; Jain, 2013; Turner, 2011). Typically, soil shear resistance is measured using calibrated laboratory equipment on collected samples by direct shear tests, unconfined compression tests or triaxial compression tests (DIN Deutsches Institut für Normung e.V, 2019; DIN Deutsches Institut für Normung e.V, 2018a; DIN Deutsches Institut für Normung e.V, 2018b). For direct field measurements hand held equipment like the Field Vane Test (FVT) or the pocket vane/torvane are commonly used to conduct shear vane tests (Turner, 2011; Crooks and Pye, 2000; Nand and Willatt, 1998; Scheres et al., 2018). With regard to shear strength measurements in wetlands, the torvane seems unsuitable due to the inaccurate approximation of the undrained shear strength (Jafari et al., 2019). Although the hand held field vane is an easy to transport and use method, measurements are not reproducible given that their operation is highly dependent on the individual (Jafari et al., 2019; Schaeffers and Weemees, 2012). Furthermore, they solely yield a single maximum shear resistance value of the soil surface they are used on and results are comparable only to a limited extent due to different measuring principles, leading to great uncertainties when trying to draw general conclusions (Jafari et al., 2019). A detailed, temporally resolved assessment of soil shear resistance remains elusive with such a device. Temporally well-resolved information of shear resistance, either plotted against rates of rotation or absolute time of operation, both of which have a decisive influence on the analysis and evaluation of the measurement outcome, could pave the way to obtain crucial insights regarding effects due to vegetation health, root-soil system structure, nutrient availability, land management and grazing. With such data, informed decisions towards a more ecosystem strengthening and soil conserving land management could become viable. Coastal engineering and protection could benefit especially from such information, given that salt marshes add towards dike toe stability and dissipate impeding ocean energy fluxes, dampening structural loads and erosion (Keimer et al., 2021). Nature based coastal protection approaches play an ever increasing important role against the background of ubiquitous climate change and rising sea levels (Ford et al., 2016; Gracia et al., 2018; Schoonees et al., 2019; Schüttrumpf and Scheres, 2020; Staudt et al., 2021; Sterckx et al., 2019; Temmerman et al., 2013; Zerbe, 2019). Consequently, a more technical and scientific approach towards the acquisition of field measurements of shear resistance of undrained soil seems warranted. In addition, modernizing the FVT appears to be particularly useful because of the many prior studies (Jafari et al., 2019). In this way, previous data sets on soil shear strength can be expanded and further scrutinized according to newly acquired knowledge regarding soil-root system interactions. This specifically requires the following objectives to be addressed: (i) provide a method less sensitive to operator errors and experience, to make observations reproducible, consistent and reliable; (ii) decipher currently not investigated temporal development of shear resistance over time; (iii) investigate coastal environments with their demanding surroundings due to heterogeneity, temporary flooding and difficult terrain regarding their soil resistance properties and to (iv) identify impacts of varying land management, namely grazing intensities; (v) provide an initial assessment of how differently managed foreshores contribute to coastal protection by ecosystem services as the root reinforcement of soil.

2. Methods

2.1. Measuring technique for shear strength assessments

For the assessment of the erosion resistance of salt marsh soils and the associated influence of grazing management, shear resistance measurements were carried out employing a specifically-developed instrumentation, named Digital, Computer-aided, automatic measurements of soil shear resistance using torque and rotation angle sensors as well as a remotely operated vane (*DiCoastar*), in salt marshes with differing grazing intensities at the German Wadden Sea. The *DiCoastar* enables computer-aided measurements of soil shear resistance using torque and vane rotation angle sensors and a remotely operated vane, which allows the user to automatize and machine-control the measurement process while also leading to a reduction of operator errors and less subjectivity of the measurements. Major components of the *DiCoastar* for shear resistance measurement, data acquisition and analysis are a geared motor (DSMP420, Drive-System Europe Ltd.), a gearbox (8GBK, DKM Motor Co.), a rotating torque sensor (DR-2212-P, Lorenz Messtechnik GmbH), an interchangeable shear vane and a control box with an integrated Raspberry Pi (3 Model B+) for control and data acquisition, all attached to a tripod with a guide rod (Fig. 1).

The device development was specifically geared towards high field reliability, especially for measurements in vegetation-covered soils. Additionally, its comparatively low foot print and minimalist invasive method make it suitable for applications in very demanding environments such as nature reserves, dunes or in near-shore areas. The measuring principle is based on international standards for in-situ soil strength measurements with a field vane (such as DIN Deutsches Institut für Normung e.V, 2021; Standards Australia, 2001; ASTM International, 2016; British Standards, 1990; Indian Standard, 1978 and NZ Geotechnical Society Inc., 2001) taking into account the design of the rod-vane connection, the selected vane size, the constant rotation speed and the underlying calculation equation of the undrained soil shear strength with suitable factors. As shear strength obtained with the hand held methods outlined in the above referenced guidelines is a single maximum value and contains no additional information, the *DiCoastar* is a significant evolutionary step forward. The *DiCoastar*'s capability to log the temporal shear stress development in response to rotation angle constitutes a major improvement with added information benefits and further research potential regarding detailed soil mechanical properties in the time domain. The novel *DiCoastar* facilitates the goal to standardize measurements in the field, as the integrated data logger now fully records rotation angle of the geared motor and time of operation in conjunction with measured torque. The measured torque is converted into shear resistance, following accepted guidelines (DIN Deutsches Institut für Normung e.V, 2021; Standards Australia, 2001; ASTM International, 2016), yielding a time-rotation dependant shear resistance development signal. To convert these time-histories of shear stresses measured with the *DiCoastar*, analogous to data obtained with a hand field vane test, the peak value of shear resistance can be readily used for comparison.

The select vane shape used in this study is a rectangular vane of $H/D = 2$ where H is the vane height and D is the vane diameter. The following equation determines the undrained shear strength s_u, calculated from the maximum torque T_{max} (DIN Deutsches Institut für Normung e.V, 2021; ASTM International, 2002; Standards Australia, 2001), it reads:

$$s_u = \frac{6T_{max}}{7\pi D^3} \tag{1}$$

The *DiCoastar* device has been tested in here, using measurements in the *A*-horizon of the soil, that typically represents the mineral soil layer in a depth of 5 cm to 25 cm and is commonly referred to as the 'surface soil' (Schoonover and Crim, 2015). For salt marshes at the North Sea, Hulisz et al. (2013) classified the surface soil layer in high marshes as *Ah*-horizon, i.e. *A*-horizon enriched with organic matter.

For calibration purposes the conversion relating motor speed and rotational rate of the shear vane was obtained from laboratory-tests; recursive tests were performed addressing the entire drive train from the motor axle, via the gear box to the vertical pole to which end the shear vane was mounted. The laboratory investigations allowed calibrating the *DiCoastar* against homogeneous sand samples of known density (1.2 kg m^{-3}) for ensuring consistent and reliable data acquisition. Samples were prepared with the help of a vibrating table in accordance to accepted guidelines (ASTM International, 2016; DIN Deutsches Institut für Normung e.V, 1996) using a single fraction sand with of 0.002 mm average diameter. In a second step, obtained *DiCoastar* shear strength values were compared against measurements conducted with a hand held device (FVT). Both instruments were operated at an identical constant measurement depth to ensure comparability.

The torque sensor was factory-calibrated to a sensor accuracy of 0.1%. For the correct implementation of the measurements and a reliable interpretation of the obtained results, a standard operation procedure (SOP) protocol is mandatory, in which the boundary conditions of the in-situ measurements are recorded. Such SOP was developed in the course of this work. The relevant boundary conditions include (i) the applied vane size, (ii) the motor settings, (iii) the measurement depth and (iv) further notes about the measuring procedure like conspicuous features, for example regarding the insertion of the vane (depth, inclination with respect to earth's g-vector, overlaying root system). Furthermore, a short description of the measurement location regarding geographic position, date-time and ambient conditions as well as predominant vegetation species is required for consistent and comparative data analysis. The python-based data analysis script of the *DiCoastar* provides an on-site visualization of torque measurements over time and rotation angle, thereby enabling a verification of the rotation speed in operation and an in-depth evaluation of shear resistance curves obtained. Raw data was recorded at a rate of 50 Hz. Data processing and filtering removed outliers above a threshold of $\geq 3\sigma$ (a value that represents the mean plus three times the standard deviation) to improve signal to noise ratio of the very sensitive torque sensor.

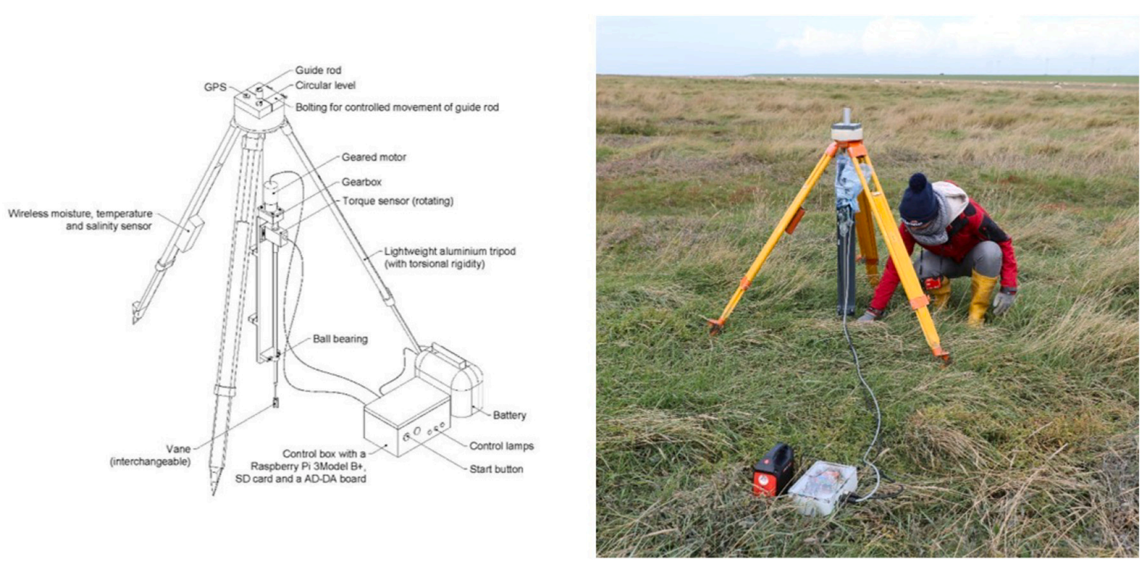

Fig. 1. Components and assembled design of the measuring device DC for gathering shear resistance over time or rotation angle.

2.2. Pilot sites and field method

The German North Sea coast is a temperate climate zone and harbors various unique and precious ecosystems, with salt marshes located along the dike foreland of the mainland and backbarrier tidal flats. The properties and appearance of the salt marshes differ with geographical setting depending on the latitude, coastal location, geology and on anthropogenic factors such as coastal zone management (e.g. grazing management, clay pits), accessibility to tourists, national protection plans and land use. Salt marshes, based on this scheme, are therefore classified either as foreland salt marshes, sand salt marshes, estuarine salt marshes, lagoon salt marshes or Halligen (Stock et al., 1998). Furthermore, the grazing management of salt marshes can be distinguished as ungrazed (semi-natural), lightly grazed (<0.3 sheep/ha), moderately grazed (0.3 sheep/ha to 0.7 sheep/ha) and intensively grazed (>0.7 sheep/ha) (Harvey et al., 2019; Kleyer et al., 2003; Nolte et al., 2013; Stock and Hofeditz, 2003). As pilot sites, two foreland salt marshes at the German North Sea coast were selected (Fig. 2): The Cäciliengroden salt marsh, an ungrazed salt marsh, and the Sönke-Nissen-Koog subdivided into areas that are moderately grazed (0.7 sheep/ha) and intensively grazed (9 sheep/ha). Both sites are characterized by soils consisting of mainly silt and clay, but differ in grazing conditions, allowing the investigation of a potential influence of grazing management on soil stability and vegetation cover (see Table 1). These foreland salt marshes are particularly relevant from a coastal engineering point of view, since design values like wave attenuation and erosion resistance contribute to dike stability and coastal protection (Bouma et al., 2007; Maza et al., 2020; Möller et al., 2014; Keimer et al., 2021).

In total 46 in-situ *DiCoastar* measurements of soil shear resistance were acquired in October 2019 (see Table 1), whereby the total number of measurements correlates with the available time on site and the required time of approximately 9 min per measurement. A vane diameter of 2.5 cm was selected in order to allow comparison with hand held vanes. Individual measurement duration and rotation speed were set to 60 s and 4 $^{\circ}$ s^{-1}, respectively. Furthermore, the top 10 cm of salt marsh soil were exclusively assessed with the *DiCoastar*, since soil erosion in salt marshes is characterized by surface processes and sediment transport induced by waves and currents (Ford et al., 2016; Crooks and Pye, 2000; Barausse et al., 2015; Christiansen et al., 2000). To that end, excess plant material above the soil surface was firstly removed manually, and then the shear vane was driven into the surface soil layer for shear assessments.

The density of the measurement points is selected such that the obtained results are assessed as suitable to reflect the respective area, including local variances due to soil heterogeneity, but without producing any interference between the measurements. In European standards, the recommended spacing of measuring points for ground investigations ranges from 15 m to 200 m. If a detailed insight into the complexity and variability of the soil at site is sought, the number of measuring points needs to be increased (CEN, 2007). Therefore, *DiCoastar* measurements were conducted in a grid pattern at 5 m intervals in each investigated salt marsh area, as shown in Figs. 4-6b).

One pilot site was the Cäciliengroden salt marsh situated inside the Jade Bay near Wilhelmshaven (see Fig. 2c). The site is located within the Wadden Sea National Park of Lower Saxony, Germany. Situated in front of a dike and in an area mostly sheltered of incoming wind waves, this salt marsh extends across a 400 m wide foreland. Another feature of this salt marsh, as part of a former cultivated landscape, is the high plant diversity and dense cover of vegetation resulting from the absence of a grazing management. Furthermore, this salt marsh is characterized by a

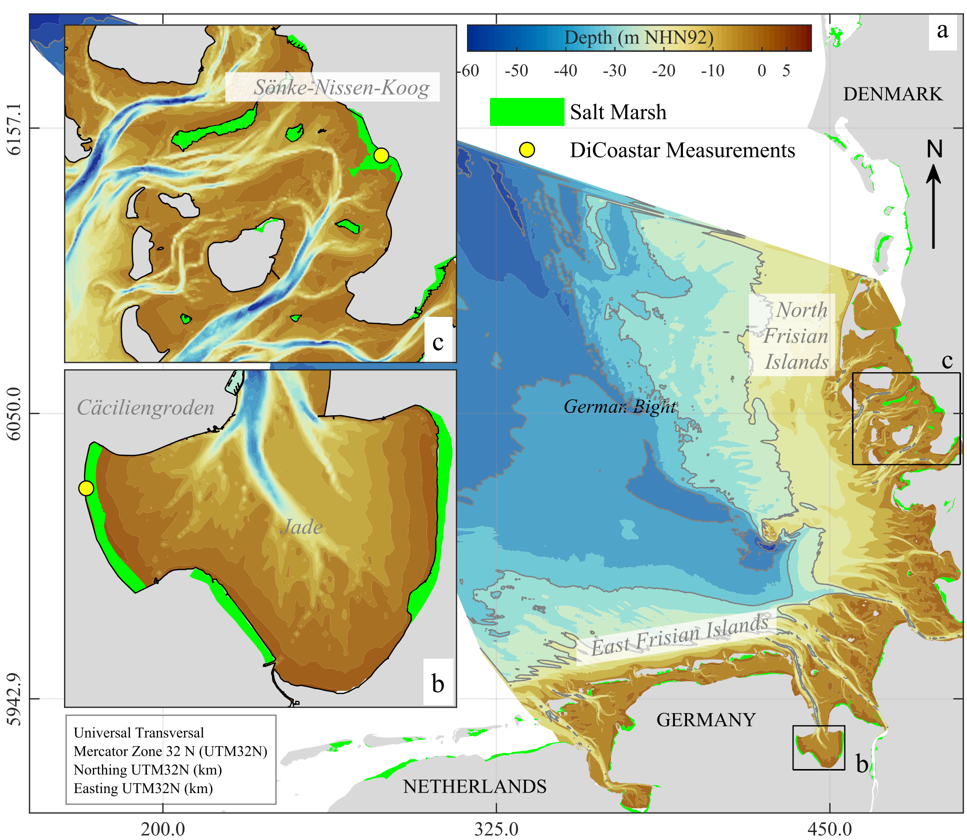

Fig. 2. Pilot sites within the German Bight (a), these comprise the Sönke-Nissen-Koog (b) located in Schleswig-Holstein, and Cäciliengroden (c) located in Lower Saxony. Bathymetric data is provided by the Federal Maritime and Hydrographic Agency of Germany (BSH) www.geoseaportal.de/. Extent of salt marsh areas are taken from Mcowen et al. (2017). https://data.unep-wcmc.org/datasets/43.

Table 1
Summarized overview of *DiCoastar* measurements in the present field study with details about the test conditions regarding the location and elevation (above mean high water) of each measuring spot and soil sampling, the grain-size distribution, the predominant vegetation as well as the select vane size, rotation speed and testing depth.

Salt marshes as pilot sites for field trials with the *DiCoastar*				
Pilot site	Cäciliengroden	Sönke-Nissen-Koog		
Management conditions	ungrazed	moderately grazed	intensively grazed	
No. measurements	16	15	15	$\sum 46$
Sampling location (UTMx/UTMy, m)	437,261.3227/ 5,926,895.0823	491,122.7755/ 6,051,961.9508	491,024.044/ 6,051,897.6222	
Elevation above mean high water (m)	0.41	0.39	0.37	
Grain-size distribution sand/silt/clay (%)	9.8 33.5 56.7	9.5 54.4 36.1	14.8 57.9 27.3	
Predominant halophyte species	*Elymus* spec.	*Atriplex portulacoides*	*Puccinellia maritima*	
Vane size (cm)	$H = 5$ $D = 2.5$			
Rotation rate (° s^{-1})	4			
Test duration (s)	60			
Test depth (cm)	top 10			

gently sloping topography with an inclination of 0.5875 and a fluent transition to the tidal flat. As a result, a salt marsh zonation is formed, which is segmented into different vegetation areas (low, mid and high marsh) due to different soil salinity and flooding frequency (Armstrong et al., 1985). In the Cäciliengroden salt marsh, 16 measurements were conducted in the upper high marsh in the immediate vicinity of the dike toe (approximately 0.41 m above the mean high water), where primarily *Elymus spec.* Stocks were found (Liu et al., 2021; Piayda, 2008). Surface soil in this area is classified as clay with a grain-size distribution of 9.8% sand, 33.5% silt and 56.7% clay (Benne et al., 2008).

The other pilot site was located in the Sönke-Nissen-Koog salt marsh (Fig. 2b) within the Schleswig-Holstein Wadden Sea National Park, Germany, and is also classified as foreland salt marsh. In contrast to the Cäciliengroden salt marsh, the topography and vegetation cover of the second pilot site is characterized by artificially built sedimentation fields (i.e. predominantly made of brushwood fences) and a preponderance of low and mid marsh zone (for more information, see (Gettner et al., 2000; Kiehl and AG Geobotanik Schleswig-Holstein und Hamburg, 1997)). Consequently, the area exhibits a much smaller inclination angle of 0.051. Since 1988, the intensively grazed Sönke-Nissen-Koog salt marsh with stocking rates of 9 sheep/ha (Stock and Hofeditz, 2003; Kiehl et al., 1996) is divided into areas with different grazing intensities to study potential influences on the vegetation cover. To identify changes in soil erosion resistance due to different grazing intensities, 15 in-situ measurements of soil shear resistance were carried out using the *DiCoastar* both in a moderately grazed area (approximately 0.39 m above the mean high water) and in an area with high grazing intensity (approximately 0.37 m above the mean high water) of the Sönke-Nissen-Koog salt marsh (Suchrow et al., 2012; Wanner et al., 2014). The surface soil consists of a clay layer with a thickness of 0.3 to 1.4 m lying on silty to sandy subsoil (Schröder and Lüning, 2000). In the moderately grazed area, the surface soil (upper 0.1 m) consists of silty clay with a grain-size distribution of 9.5% sand, 54.4% silt and 36.1% clay, whereas in the area with high grazing intensity, the surface soil is more a silty clay loam with a grain-size distribution of 14.8% sand, 57.9% silt and 27.3% clay (Nolte et al., 2013). The vegetation cover of these areas with divergent grazing intensities differ in terms of species composition and vertical density. Studies by (Suchrow et al., 2012; Wanner et al., 2014) reveal the alterations in plant diversity and the predominant halophyte species in the vegetation cover due to changes in grazing pressure at the measurement sites of the Sönke-Nissen-Koog salt marsh between 1988 and 2007. In 1988, both areas of the salt marsh were intensively grazed and *Puccinellia maritima* was the predominant halophyte species with a coverage of 60% to 70%. Until 2007, the predominance of *P. maritima* in the salt marsh area with persistently high grazing pressure decreased slightly to a coverage of 30% to 50%. In addition, an increase in coverage by the halophyte species *Atriplex portulacoides* (10% to 30%) and *Glaux maritima* (10% to 20%), both low-growing plant species, was identified. In the vegetation cover in the salt marsh area, where grazing pressure has been reduced since 1988, the number of predominant halophyte species increased to three consisting of *P. maritima* (with a coverage of 2% to 50%), *A. portulacoides* (with a coverage of 10% to 40%) and *Aster tripolium* (with a coverage of 10% to 50%). At all pilot sites, shear resistance measurements were situated in the upper part of the salt marshes to ensure comparability of the obtained results and, moreover, to focus on the immediate vicinity of the dike, as this area and the associated erosion resistance and wave damping potential are affecting the dike stability.

2.3. Laboratory measurements of soil characteristics

Additionally to the *DiCoastar* measurements, exemplary soil samples were taken from the pilot sites for laboratory testings, as the undrained shear strength of soils is strongly influenced by soil moisture content and mineralogical soil properties (Brooks et al., 2021; Ghosh, 2013; Schlue et al., 2007; Watts et al., 2003). Both soil samples obtained from the field were extracted from a central point of the areas, where measurements of soil shear resistance were conducted (see Table 1, Sampling location). With regard to the Sönke-Nissen-Koog salt marsh, the moderately grazed area was chosen for soil sampling. Soil moisture content was determined by oven drying (DIN Deutsches Institut für Normung e.V, 2015), where samples are dried at 105 °C until constant mass is reached, and reported on a dry basis. Afterwards, the loss on ignition (DIN Deutsches Institut für Normung e.V, 2002) is measured from the samples by storing them in an oven at 550 °C for a minimum of 2 h, indicating the organic matter content of the soil samples.

3. Results

3.1. Laboratory calibration of DiCoastar

In preliminary laboratory experiments with the *DiCoastar*, time-histories of shear resistance were measured in undisturbed sand samples. These samples were consistently synthetized in a geotechnical laboratory to ensure identical soil conditions across test batches. The resulting shear resistances as a function of the rotation angle are presented in Fig. 3, with the rotation angle indicating the angular position of the vane in the soil in relation to the initial position. Since the rotational speed of the vane remains constant, the time to failure can be expressed in both degrees and seconds, indicating the phase length from

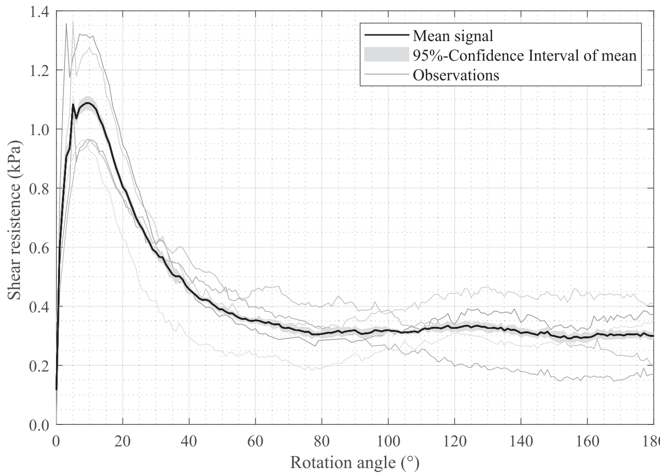

Fig. 3. *DiCoastar* measurements showing shear resistance curves over rotation angle acquired in undisturbed, homogenized sand samples with predefined density for a rotation angle from 0% to 180%.

the start of the motion, initiating a torque acting on the vane until the maximum torque or shearing is reached. Data were curated through filtering and despiking prior to plotting, while the mean of the conducted tests is also presented along with the confidence intervals. The graphs generally exhibit a steep increase from 0% to 10% reaching their respective maximum value ranging around 1 kPa, and these values indicate the maximum shear strength of the investigated sand samples. The maximum shear resistance can be associated with a sudden failure of the grain structure after initial deformation induced by the onset of rotation; this is characterized by the grains of the soil matrix close the vane edge to shear against their neighbouring grains outside of the vane geometry.

Subsequently, a smooth decline of shear resistance after reaching the point of failure is observed over an angle of rotation between 10% to 90%. Shear resistance over time or rotation angle is calculated from the torque measured by the *DiCoastar* using Eq. (1) for undrained soil shear strength (DIN Deutsches Institut für Normung e.V., Standards Australia, ASTM International). For undisturbed and compacted samples of sand, shear strength reaches a value of 1.1 kPa on average (Fig. 3). Surpassing a rotation angle of 90 $^{\circ}$, the *DiCoastar* measurements oscillate around a baseline value of 0.3 kPa, where solely grain-shear exhibits any resistance but the larger soil matrix is disturbed and offers no more shear resistance. The average shear strength value measured with the *DiCoastar* was slightly (16%) higher than in the corresponding measurements with a hand held field vane (FVT). Results obtained with a lab-vane (Fully Automatic Laboratory Vane Shear Tester, Wille-Geotechnik) resulted in similar trajectories although with significantly less repeatable measurements than was attained with the *DiCoastar*. Passing these initial laboratory-based tests of the new *DiCoastar* and showing a high degree of consistency, the equipment is considered calibrated against established laboratory methods and is ready for field tests.

3.2. Field measurements at pilot sites

The subsequent section introduces results obtained from field measurements at the pilot sites in Northern Germany (Fig. 2). Results showcase for the first time temporally resolved shear resistance of salt marsh soil. Results are scrutinized regarding their location specific signal form, peak shear strength and are clustered given their environmental settings ranging from ungrazed (semi-natural) to intensively grazed areas. Furthermore, predominant halophyte species as well as plant communities are identified and plant diversity of the vegetation cover is assessed, to ensure comparable measurement results. For the sake of comparable measurement sites, salt marsh areas situated in close vicinity of the dike toe are selected. Field measurements were conducted over a period of two days in October 2019 (see Table 1).

3.3. Vegetation cover

At both pilot sites multiple measurements were conducted amounting to a total of 46 at Sönke-Nissen-Koog and at Cäciliengroden (see Table 1). Regional distinction in local vegetation cover, density and diversity were apparent and noted as follows. Cäciliengroden featured a high degree of canopy closure and a large diversity in plant species, which exhibited a distinct salt marsh zonation. Sönke-Nissen-Koog, in comparison, exhibited a smaller diversity in plant species, which is likely attributable to the active grazing management, which is absent at the other pilot site. Within the pilot site Sönke-Nissen-Koog areas with different grazing intensities are delineated (Stock et al., 1998; Gettner et al., 2000; Stock, 2003). Areas with a higher grazing intensity are markedly different; this shows as a shift from typical salt marsh vegetation into a meadow of short common salt marsh grass, *Puccinellia maritima*, with declining *Atriplex portulacoides* stocks. In other words, an almost complete reduction in the vertical density distribution of the vegetation cover is observed in the salt marsh area with high grazing pressure.

The vertical density distribution of the vegetation cover in salt marshes is negatively correlated to grazing pressure (Adnitt et al., 2007; Brooks et al., 2021; Davidson et al., 2017; Andresen et al., 1990; Stock, 2011). Nevertheless, areas in the salt marsh with divergent grazing intensities show a recovery of vegetation diversity and density within one vegetation period, especially in areas where grazing was stopped (Bredemeier et al., 1999; Stock, 2011). This reflects the fact that the presence of remaining below-ground vegetation material, which has the ability to maintain biodiversity, allows vegetation which is sensitive to grazing, e. g. *Elymus spec.*, to recover, spread and grow again after a cessation of grazing (Bockelmann and Neuhaus, 1999; Amiaud et al., 2008).

Although the positioning of the measuring spots (see Figs. 4-6b) is based on comparable salt marsh areas, these differ in terms of the predominant plant community. The measuring spots in the semi-natural, ungrazed salt marsh at Cäciliengroden are characterized by a dense *Elymus* meadow as part of the plant community *Agropyretum-Festucetum litoralis*. The predominant plant community along the measuring spots of the moderately grazed area at Sönke-Nissen-Koog is formed by *A. portulacoides*, while *P. maritima* predominates in the intensively grazed area of the salt marsh (Gettner et al., 2000). In summary, local biodiversity is not directly affected by grazing, but the quantity of plant species reacting sensitive to grazing decreases in the canopy thus reducing vertical and horizontal elements in the vegetation structure (Boorman, 2003; Hofstede, 2003; Leuschner and Ellenberg, 2017).

3.4. DiCoastar shear resistance measurements

Figs. 4-6 show results of shear resistance measurements over time and rotation angle, respectively. The results are scrutinized for each pilot site, with individual types of shear resistance curves identified at both pilot sites. The main focus of the *DiCoastar* method is the mapping of the shear resistance curve, specifying the times of failure, in order to be able to investigate such complex processes as are to be expected in a soil-root matrix. Hence, results include information on the measured shear strength as well as the associated times of the structural failure expressed as rotation angle or time of measurement. This indicates a delayed shearing or failure of the soil-root matrix due to soil-root system interactions. For the respective groups of curves, mean values of the vane rotation angle ('mean angle') or the measurement duration ('mean time') at the time of the identified failure of the soil structure are therefore distinguishable and compiled in Figs. 4-6. Measurements were conducted for 60 s each, with peak values being reached at around 2 s to 6 s and signals oscillating at lower values on average, after reaching

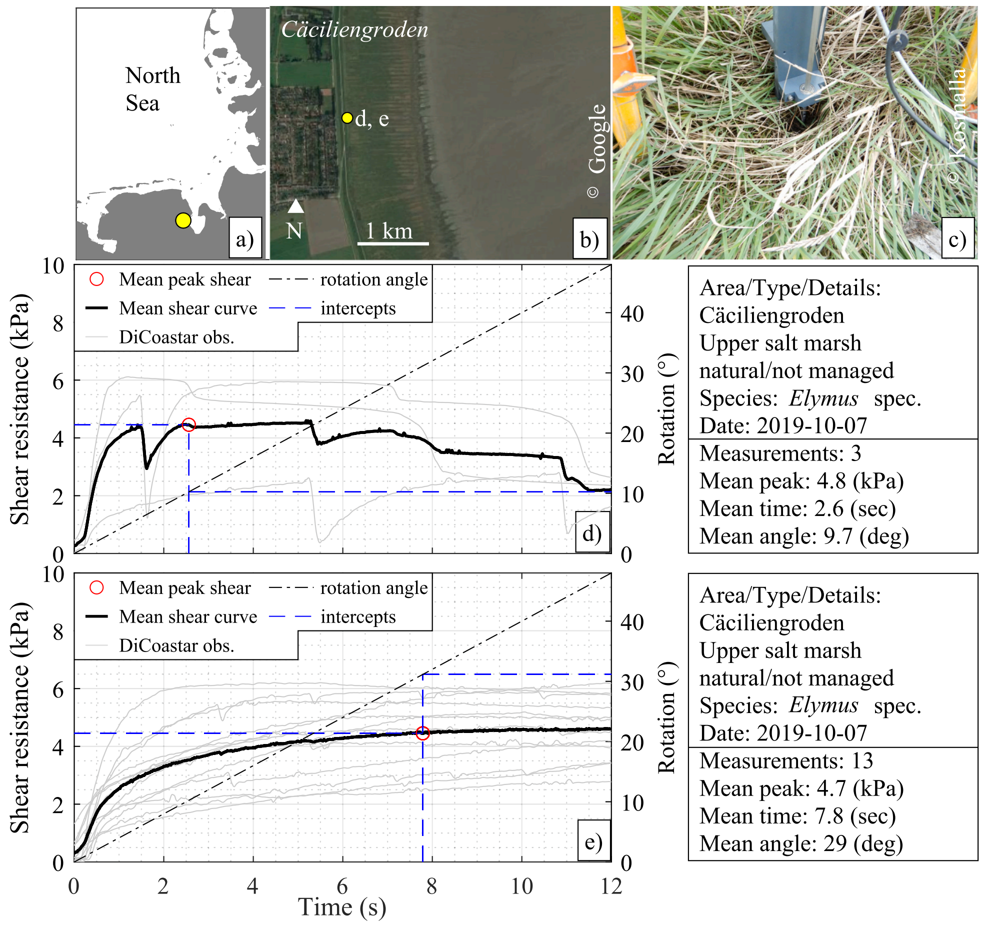

Fig. 4. *DiCoastar* measurements for natural, ungrazed salt marsh at Cäciliengroden, Germany. (a) Location in relation to the German Bight. (b) Location in the foreland salt marsh. (c) Graphical representation of a typical measuring spot. (d) Type 1 results and (e) Type 2 results. Background image for (b) is provided by Google Maps, accessed through Quantum GIS. GeoBasis-DE/BKG, GeoContent, Maxar Technologies, Map data 2021 GeoBasis-DE/BKG ©2009, Cäciliengroden. UTMx 438,646 UTMy 5,925,854, scale 1:8000, EPSG: 25832, accessed: 26.03.2021.

failure. In this context, and unlike the described failure for the uniform sand samples in the laboratory testing, failure is referred here to as the loss of strength as a result of the grain-root matrix to yield upon vane motion in the soil. This specific failure inside the soil and the complexity of the surface soil layer matrix will have to be investigated further, but is generally beyond the scope of this work. Given this general pattern, results are shown to the extent of 12 s, to cover the peak shear strength development and failure with ensuing oscillation representative for the remaining measurement cycle. To ensure comparability of the results, all measurements were performed in salt marsh areas located close to the dike separating the salt marshes from the hinterland to ensure closely matching soil conditions. Field data show considerable differences compared with typical shear resistance curves for undisturbed soils revealing the influence of root systems on soil shear resistance and biostabilization processes. Moreover, patterns are discovered in the data that allow a classification of the results into types of curves and also represent an important and unique result of this field study, as it enables insights into specific soil-root system interactions. In this study, two different types of shear resistance curves are identified and analyzed for each study area.

The biostabilization processes induced by the root system result in soil failure mitigation by the following four characteristics, which can occur separately or in combination:

Shear resistance curve characteristics

i. Sigmoidal function before reaching maximum value of shear resistance (shear strength)
ii. Sigmoidal downward-sloping after passing maximum value of shear resistance (shear strength)
iii. Step-wise reduction of shear resistance beyond the peak value with multiple points of partial failure
iv. Unspecific/undetectable point of total failure

Based on the above characteristics of shear strength evolution, *DiCoastar* measurements are divided into types of curves for each study area and classified according to these four characteristics. The pilot sites are presented in increasing grazing intensity, starting with Cäciliengroden and transitioning to Sönke-Nissen-Koog.

The results of shear resistance measurements over time or rotation angle in the ungrazed saltmarsh at Cäciliengroden are illustrated in Fig. 4. Two different signal types are identified, with the first type 1 given in Fig. 4 d) to which characteristics (i)-(iii) can be assigned. In particular, due to multiple points of failure and a step wise decrease of soil shear resistance. The type 2 curve of shear resistance measurements at Cäciliengroden given in Fig. 4 e) shows a flat signal curve without any significant point or peak of failure as known from undisturbed or other soils and is therefore associated with the characteristics (i), (ii) and (iv). This type represents the main type making up 81.25% of all measurements. In fact, shear resistance rather approaches a constant value over time and rotation angle facilitating comparisons with a Gompertz function once reaching the maximum shear strength (Gompertz, 1825). The average shear strength is similar for both curve types reaching values of 4.7 kPa to 4.8 kPa, respectively. The mean time and mean rotation angle at the point of failure reaches higher values for the type 2 curves (7.8 s/29 °) compared to the type 1 curves (2.6 s/9.7 °).

DiCoastar resistance measurements in the Sönke-Nissen-Koog salt marsh with areas of different grazing intensity are shown in Figs. 5 d-e) and 6 d-e), respectively. Fig. 5 represents an area of the salt marsh, that is moderately grazed, and Fig. 6 shows results obtained from an area,

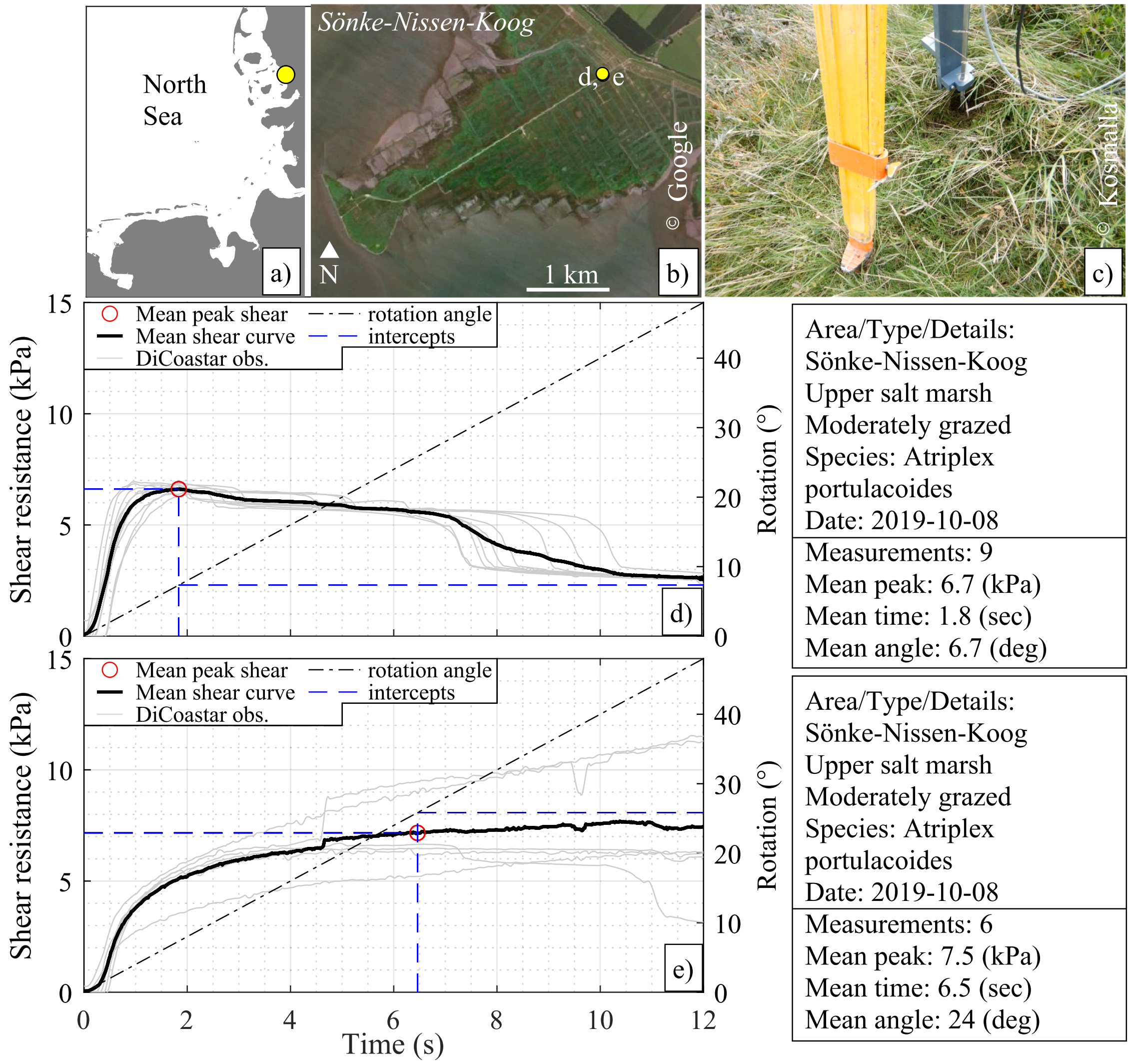

Fig. 5. *DiCoastar* measurements for moderately grazed salt marsh at Sönke-Nissen-Koog, Germany. (a) Location in relation to the German Bight. (b) Location in the foreland salt marsh. (c) Graphical representation of a typical measuring spot. (d) Type 1 results and (e) Type 2 results. Background image for (b) is provided by Google Maps, accessed through Quantum GIS. (c) 2021 Aerodata International Surveys, GeoBasis-DE/BKG,GeoContent,Landsat/Copernicus,Maxar Technologies, map data ©2021 GeoBasis-DE/BKG©2009, Sönke-Nissen-Koog UTMx 490,178, UTMy 6,051,346, scale: 1:16000, EPSG: 25832, accessed: 26.03.2021.

that was, at that time, intensively grazed by sheep. The classification of both shear resistance curve types for the moderately grazed salt marsh area is similar to the curve classifications (3.4) for Cäciliengroden (cf. Fig. 4 d-e). Nevertheless, a notable difference between the type 1 curves is evident (cf. Figs. 4 d) and 5 d)). Even though both type 1 curves show a step wise decrease of the measured shear resistance after reaching a maximum, the amount of partial failure is less in the moderately grazed area of the Sönke-Nissen-Koog salt marsh. Here, the average shear strength reaches 6.7 kPa for the type 1 curve and 7.5 kPa on average for the type 2 curve. These values are slightly higher by a factor of 1.4 to 1.6 compared to Cäciliengroden without any grazing. In contrast to this, the mean time and mean rotation angle of the determined points of failure decreases with increased grazing impact, reaching values of 1.8 s and 6.7 ° for the type 1 curve and 6.5 s and 24 ° for the type 2 curve, respectively.

For measurements conducted in an area of the Sönke-Nissen-Koog salt marsh intensively grazed by sheep, the classification (3.4) of both identified curve types in the shear resistance measurements is slightly adjusted. Considering the type 1 curve, the step wise decrease of the measured shear resistance after reaching a maximum value shows notable oscillations (cf. Fig. 6). An exact maximum value of the shear resistance can be determined for the type 2 curve, the classification (vi) is omitted here, so that only the classifications (i) and (ii) apply. The shear strength measured in the intensively grazed area of the Sönke-Nissen-Koog salt marsh reaches considerably higher values of 14 kPa for the type 1 curve and 11 kPa for the type 2 curve than the corresponding measurements in salt marsh areas without (high) grazing pressure. Moreover, when comparing the shear strength measured in the Sönke-Nissen-Koog salt marsh with areas of different grazing conditions, a more marked increase of soil shear strength by a factor of 2.34 to 2.92 is observed when the sheep grazing management is intensified. Regarding the mean time and mean rotation angle at the point of failure, no noticeable differences are observable comparing the type 2 curve of the intensively grazed area (6.4 s and 23 °) with the type 2 curve of the moderately grazed area (6.5 s and 24 °) of the Sönke-Nissen-Koog salt marsh. Considering the type 1 curves, these values increase to 3.4 s and 12 °, respectively, in the salt marsh area with high grazing pressure and is thus slightly higher than in the ungrazed/moderately grazed salt marsh areas. Assessing the overall distribution between type 1 and type 2 curves, the pilot site Sönke-Nissen-Koog is more even with 15 of each type, whereas Cäciliengroden shows a more pronounced type 2 response, with 13 to 3 type 1.

For the moderately grazed area, 60% pertain to type 1 curves and 40% fall within the type 2 classification. For the intensively grazed area, this ratio is reversed. Hence, only for the measurements in

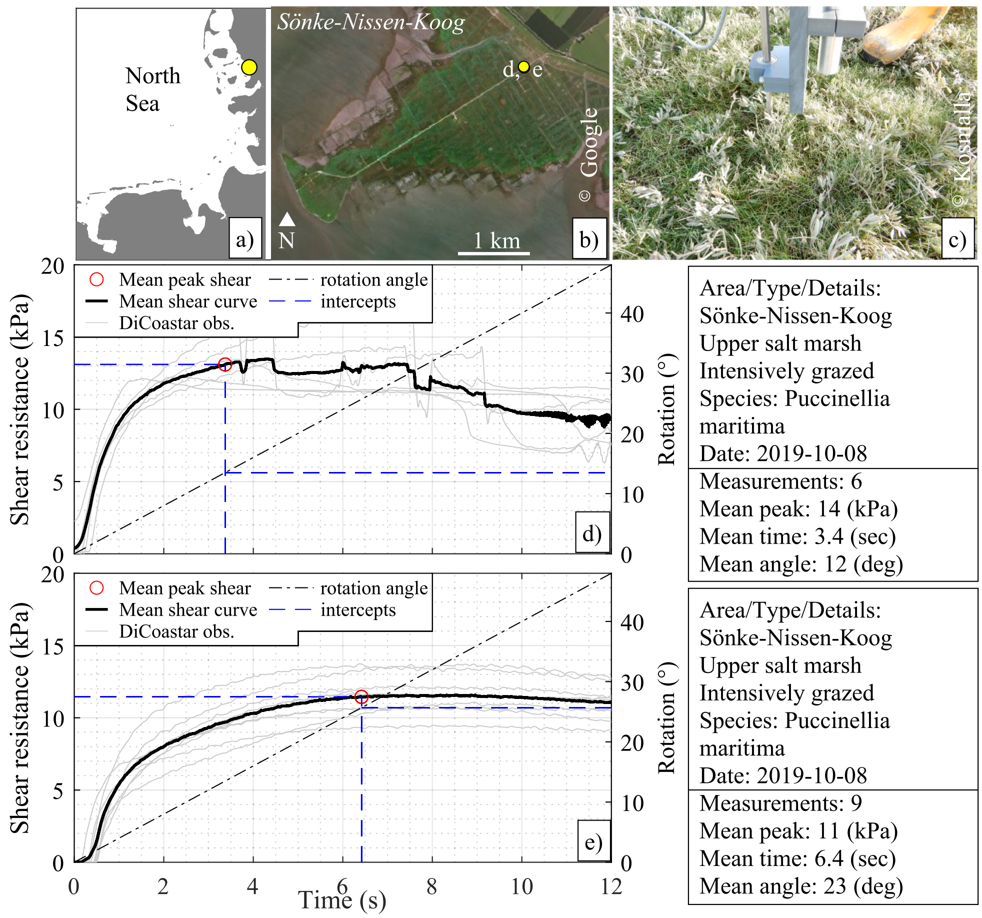

Fig. 6. *DiCoastar* measurements for intensively grazed salt marsh at Sönke-Nissen-Koog, Germany. (a) Location in relation to the German Bight. (b) Location in the foreland salt marsh. (c) Graphical representation of a typical measuring spot. (d) Type 1 results and (e) Type 2 results. Background image for (b) is provided by Google Maps, accessed through Quantum GIS. (c) 2021 Aerodata International Surveys, GeoBasis-DE/BKG,GeoContent,Landsat/Copernicus, Maxar Technologies, map data ©2021 GeoBasis-DE/BKG©2009, Sönke-Nissen-Koog UTMx 490,178, UTMy 6,051,346, scale: 1:16000, EPSG: 25832, accessed: 26.03.2021.

Cäciliengroden could the type 2 of shear resistance curves be defined as a main type. However, 28 of 46 *DiCoastar* measurements were defined as type 2 curves, in which soil shear resistance rather describes a Gompertz function than yielding a detectable point of failure (cf. Figs. 4, 5 & 6 e). In addition, the resulting delay of time and rotation angle at the peak shear strength is positively correlated to a reduction of grazing intensity. The other 18 results defined as type 1 are characterized by numerous points of partial failure (iii).

3.5. Soil analysis

Undisturbed soil samples were collected using soil sampling rings from both pilot sites on the corresponding day and analyzed in a laboratory regarding the soil moisture content reported on a dry basis and the organic matter content, both exerting a significant influence on soil shear strength (Brooks et al., 2021; Ghosh, 2013; Schlue et al., 2007; Watts et al., 2003). The results obtained from the soil analysis show a 26% higher soil moisture content in Cäciliengroden (120%) than in Sönke-Nissen-Koog (95%), which can be attributed to the differences in topography and salt marsh width. The average ignition loss of 22% obtained from a soil sample taken from the Cäciliengroden salt marsh exceeds the 18% ignition loss obtained from a soil sample of the Sönke-Nissen-Koog saltmarsh by about 22% reflecting the more natural state of the Cäciliengroden salt marsh. The comparatively low shear strength values obtained in the Cäciliengroden salt marsh can thus be partly attributed to a higher soil moisture content than in the Sönke-Nissen-Koog saltmarsh (Brooks et al., 2021; Ghosh, 2013; Schlue et al., 2007; Watts et al., 2003). However, since soil analysis was conducted on a random sample basis, the corresponding results and assumptions are based on a small data set and therefore only represent potential links.

4. Discussion

Generally, field measurements based on hand held field vanes (FVT) yield instantaneous information regarding the maximum soil shear strength (Brooks et al., 2021; Ghosh, 2013; Jain, 2013). Nevertheless, a hand guided measurement is always prone to operator errors and precludes inter-comparisons for scientific and research purposes. Furthermore, manual field vanes do not disclose any information regarding the temporal scale of shear resistance during load exertion. Especially against the background of soil erosion around the globe in conjunction with climate change and mounting anthropogenic pressures, a precise and detailed quantification of soil erosion resistance in different ecosystems is an inevitable piece of information. Such information will be crucial for a transformation of federally guided management approaches towards nature based solutions and ecosystem strengthening land management decisions. Further applications of the *DiCoastar* method in field conditions are recommended in order to ensure the required level of objectivity, detail and the reliability of field data concerning soil erosion resistance as well as their comparability between further studies, sites and soil types. *DiCoastar* results presented here for coastal salt marshes, offer new insights into vastly unexplored soil-root system interactions, and will pave the way towards understanding its resistance to external loads originating from waves and currents. What is more, the temporal record of shear resistance over rotation angle facilitates a detailed analysis and quantification of potential impacts of varying land management plans. Here the impact of varying intensities of sheep grazing are shown to have a distinct impact on the resulting shear resistance curves.

Soil shear strength was shown to correlate positively with sheep grazing intensity: The mean shear strength in the ungrazed salt marsh reaches peak values of 4.7 kPa to 4.8 kPa, whereas in the moderately grazed salt marsh area average shear strengths of 6.7 kPa to 7.5 kPa were measured, which, however, clearly undercut the mean shear strength of 11 kPa to 14 kPa measured in the salt marsh area with high grazing pressure. This positive correlation leads to the assumption that the peak erosion resistance of salt marsh soil increases with higher grazing pressure. Since the erosion resistance of the soil represents an important factor determining the potential of ecosystems to contribute to coastal protection, an improvement in the coastal protection potential of coastal marshes by a grazing management is conceivable. However, factors such as accretion or the attenuation of waves and currents need to be considered for a final assessment of the contribution to coastal protection provided by salt marshes. Nevertheless, measurements in different foreland salt marshes also indicate that soil shear strength experiences a marked increase in shear strength only under high intensity grazing. The increase in maximum shear strength of salt marsh soil from ungrazed areas compared to (moderately) grazed areas amounts to 1.4 and 2.92 times for type 1 and 1.6 and 2.34 times for type 2 respectively. In other words, a slight intensification of grazing led to an increase in measured shear strength of about 60%, while a high grazing pressure caused an increase in the mean shear strength of up to 200%. Vice versa, a cessation or even a reduction of grazing results in a decrease in measurable peak shear strength.

It has been shown, that the vertical density distribution of the vegetation cover in salt marshes is reduced by grazing (Bredemeier et al., 1999; Gettner et al., 2000; Kiehl et al., 1996). This was also observed in the present field study at the pilot site Sönke-Nissen-Koog. Positive erosion resistance effects from soil compaction due to trampling are accompanied by a reduction of soil porosity and, with it, vegetation diversity (i.e. negative environmental effects), and a decreased canopy height, which in combination result in the observed increase of shear resistance at the soil surface. This is in line with previous studies who also stated this correlation (Bouma et al., 2007; Chen et al., 2011; Ford et al., 2016; Ghisalberti and Nepf, 2006; Li and Yan, 2007; Nepf and Vivoni, 2000). In regards to dike stability, an increase in grazing results in a decrease in vegetation height and density, in turn leading to reduced wave and current attenuation provided by salt marshes (Maza et al., 2020; Peruzzo et al., 2018; Keimer et al., 2021; Augustin et al., 2009). This effect will likely increase soil erosion under storm conditions and counteracts the quantified increase in shear resistance, at least partially. Further research, ideally extended to other sites and a more diverse range of salt marsh characteristics is expected to increase the understanding of shear resistance and its positive correlation with grazing versus its potentially negative effects on run-up heights at neighbouring coastal dikes.

The developed and introduced *DiCoastar* performed well during field trials in demanding salt marsh conditions, providing an unprecedented level of consistency and repeatability, as compared to hand held field vanes (FVT). The assessment of shear resistance of vegetation-covered, undrained soils in the field proved viable and measured values are deemed reasonable given their reproducibility. An elementary result of the presented *DiCoastar* measurements is the identification of shear resistance curve types, which provide a novel insight into specific soil-root interactions. Four different curve characteristics were detected which reflect the deviations from standard shear resistance curves of undisturbed soils. These characteristics include the sigmoidal function before and after reaching a maximum value, respectively, a step-wise reduction after the peak value and thus an increased number of points of partial failure as well as an unidentifiable point of total failure. Relationships between these curve types and specific types of plants, the root tensile strength and the root length density will have to be investigated further, but is generally beyond the scope of this work. Particularly striking is the observed characteristic of ungrazed salt marsh soil, that failure and shearing of the soil is delayed or even prevented, given the shear resistance curves resemble sinusoidal functions. It is hypothesized that this phenomenon is attributable to the less compacted soil due to the absence of grazing livestock. Equally noticeable is the post-failure drop in shear resistance resembling a step wise progression indicating root breaking during shearing (Waldron and Dakessian, 1981). Despite the striking nature of these response functions, they render the determination of a point of failure and thus the definition of a single shear strength less representative. This contrasts the standard methods relying on hand held field vanes, which yield only a single value. Results presented here show that the first point of failure is followed suit by multiple points of failure with intermittent increases in shear resistance. This effect is likely caused by individual roots snapping in succession, providing a lot more shear resistance depending on root tensile strength (Jain, 2013; Waldron and Dakessian, 1981; Alam et al., 2018; Cazzuffi et al., 2014; Liang et al., 2017) than is measurable with standard hand held field vanes (FVT) yielding a single value.

An influence of soil moisture and organic matter content on the results of the present field study is difficult to quantify, given that soil conditions depend not only on the location but also on seasonality. Soil samples analyzed exhibit differences in both values, despite being collected over two days during the field trials, minimizing short term weather impacts. It is reasoned that the differences arose due to differences in geodetic height between the pilot sites, but this is not the case with both sites being nearly equally elevated at 0.37 m to 0.41 m above mean high water. Another likely factor presents the differences in canopy height, with the grazed salt marsh areas showing 20% lower soil moisture content due to less evaporation shielding caused by less vegetation coverage. Similarly, the 22% higher organic matter content in the ungrazed area is likely contributing to the retention of soil moisture in absence of livestock feeding on the plant matter.

In the ungrazed salt marsh, a layer of dead vegetation material was noticed on the soil surface leading to an heterogeneous layer of sediment and dead vegetation material (Allen, 2000). This layer formed in the absence of grazing livestock and required an adaption of the embedding depth of the *DiCoastar* vane, as it covered the soil surface. Penetrating this up to 0.3 m thick loose layer of dead plant material could add rod friction and increase measured shear resistance. However, given that the values acquired in Cäciliengroden are the lowest by a factor of 1.4 to 2.92 of all measurements and only here the layer of dead plant material was encountered, the added rod friction is considered to have a negligible impact. However, the shear resistance measurements over time or rotation angle conducted with the *DiCoastar* help to elucidate soil-vegetation interactions with regard to the root systems and the associated ecosystem service in terms of biostabilization processes for erosion protection (Haines-Young and Potschin, 2018). The validation of the *DiCoastar* with hand held equipment for in-situ measurements of soil shear strength and with a laboratory vane indicates a high reliability of the data output. The technical setup of the *DiCoastar*, detailed in Section 2.1 proves adequate for in-situ measurements of shear resistance in vegetation-covered soils setting the nominal power of the geared motor to attain $4\,^{\circ}\,s^{-1}$ (max. 2 Nm). Auxiliary parameters such as local soil moisture, temperature and salinity were not assessed during measurements presented here. These parameters could readily yield more insight into subsoil interactions and resulting soil shear resistance.

The main limitations of the *DiCoastar* method for assessing surface erosion resistance in (coastal) ecosystems is the fact that the field vane test is designed for shear strength measurements in cohesive soils and therefore excludes sandy environments. Nevertheless, the *DiCoastar* method should also be used in vegetation-covered dunes, for example, in order to allow further conclusions concerning the root reinforcement of surface soil and further system improvements. On the other hand, insertion of the vane causes root disturbance and cutting, resulting in a partially altered soil-root system structure. Such in-situ measurements of soil-root system interactions, however, are still regarded as a rarely researched method and therefore require further investigations. Especially, in combination with measurements of the root tensile strength and other relevant root parameters as well as supporting laboratory measurements of soil shear strength to further validate the method. In addition, only surface soil shear resistance can be measured by the *DiCoastar* method in its current configuration, since non-destructive measurements in deeper soil layers require a modification of the *DiCoastar* including a sheathed extension rod to avoid soil disturbances during operation. With regard to the obtained results from 46 in-situ measurements with the *DiCoastar*, more measurements, including repetitions, are required to increase sample sizes and produce statistically robust results and more detailed information concerning the root tensile strength or local variances in soil moisture is needed to enhance the comprehension of soil-root system interactions identified in shear resistance curves. Additional plant based parameters such as the Leaf Area Index (LAI) or specific root traits easily could complement shear measurements and put plant health, stress levels and associated shear resistance into perspective (de Battisti et al., 2019; Traxler, 1997; Yousefi Lalimi et al., 2017). Finally, seasonal fluctuations in soil shear resistance were not addressed yet, and might well lead to more refined deductions regarding the soil-vegetation interaction and resulting soil shear resistance.

5. Conclusion

In this work, the *DiCoastar*, a field measuring device for the assessment of local shear strength in vegetation-covered, undrained soil, is introduced. The measurement system was developed in accordance with the currently valid standard field vane test (FVT).

The *DiCoastar* was successfully calibrated and trialed in pilot field measurements. Results corroborate the objectives formulated in that (i) the new method yields reproducible results, eliminating or at least minimizing operator errors during measurements rendering data acquisition a lot more reliable; (ii) time-variant shear resistance over rotation angle is digitally recorded facilitating the assessment of temporal response functions in the field; (iii) field trials in coastal salt marsh environments, which are demanding due to a high degree of heterogeneity, temporary flooding and uneven topography are rendered possible through the *DiCoastar*; (iv) land management impacts, namely grazing, were successfully detected in between two different pilot sites of comparable salt marsh types; (v) an initial assessment of the contribution to coastal protection by soil-root system interactions in differently managed foreshores was attained.

Moreover, the digitized data acquisition was shown to provide a revealing insight into soil shearing processes in combination with soil-vegetation interactions. This measuring technique is considered a valuable addition to future field studies, not only in a coastal protection context but rather within the general framework addressing soil erosion and land management. The design of the *DiCoastar* can be extended for greater applicability by easily changing the vane dimension and form or even by considering different force directions (Comino and Druetta, 2009).

However, all results and resulting statements presented here are only potential links, as considerably more measurements are required for statistically robust statements. In addition, an implementation of longer field measurement series and the improvement of the workflow using the newly developed *DiCoastar* are needed for the generation of a sufficient number of measurements for statistically relevant statements and are therefore subject of ongoing research.

Results presented here for impacts of divergent grazing management indicate that the shear strength of salt marsh soils increases with intensified grazing conditions. However, the shear resistance curves expressed over time and rotation angle show that the point of failure is delayed in salt marshes without grazing management due to soil-vegetation interactions contributing to erosion resistance. Besides this, the vegetation cover of these more natural salt marshes show higher densities in the vertical distribution of the vegetation cover and, thus, are assumed to provide a significantly stronger decrease in flow velocities at the soil surface resulting in decreased shear forces (Carus et al., 2016). The presumption that grazing enhances the erosion resistance of salt marshes by soil compaction (Brooks et al., 2021; Davidson et al., 2017; Stock et al., 1998; Pagès et al., 2019) should be re-investigated based upon results presented here. The same holds true for the hypothesis that cessation of grazing in foreland salt marshes is expected to enhance the dike stability.

The *DiCoastar* is ideally suited for expanding current studies focusing on the erosion resistance of salt marshes and the contribution of root and rhizome systems to biostabilization (e.g. van Eerdt, 1985). Moreover, a comprehensive application of this method enables a comparable data set through repeatable and detailed measurements. These data on soil-root interactions are also of interest for many research areas, such as coastal protection, soil bioengineering, agriculture, forestry and ecosystem strengthening land management.

For the analysis of seasonal fluctuations in soil-vegetation interactions, in-situ measurements at specific sites distributed over the year need to be conducted revealing the seasonality of the soil and vegetation properties in dependence on specific vegetation types. It is recommended to use the *DiCoastar* for further shear resistance measurements in vegetation-covered soils, since the time-rotation dependant analysis of shear resistance provides a decisive insight into the soil-vegetation interactions and the measurement system is suitable for field trials in very demanding environments such as densely vegetation-covered areas or, moreover, nature reserves due to the nearly non-destructive testing procedure.

New insights introduced here, present a viable option to consistently assess shear resistance under field conditions for different seasons and coastal ecosystems to decipher their individual mechanics and responses towards different management approaches. Further advancing the *DiCoastar* prototype by adding auxiliary sensors will possibly lead to new insights and allow to identify eventual ecosystem co-benefits dependant on management approaches, seasonality and stress levels. Finally, a consistent and reliable data base of such coastal ecosystem erosion resistances and complimentary information could readily contribute towards integrating nature based coastal defense approaches into national coastal defense guidelines and SOPs by highlighting their invaluable contributions towards coastal protection to combat erosion tendencies.

Data statement

Code and data can be acquired from the corresponding author upon reasonable request.

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CRediT authorship contribution statement

Viktoria Kosmalla: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft. **Kara Keimer:** Investigation, Data curation, Writing – review & editing. **David Schürenkamp:** Conceptualization, Methodology, Software, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Oliver Lojek:** Data curation, Writing – original draft, Writing – review & editing, Visualization. **Nils Goseberg:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare no competing financial interests.

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