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Optical Remote Sensing of Microphytobenthic Biomass: a Method to Monitor Tidal Flat Erodibility

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With 9 Text-Figures and 1 Table

Key words: Optical remote sensing, erosion, shear stress, benthic diatoms, benthic chlorophyll *a*, fine grain-size.

Abstract

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A basis to monitor erosion shear stress of tidal flat surfaces by means of optical remote sensing has been developed. Erosion shear stress and corresponding bio-geochemical parameters of different tidal flats were measured during five years in the Sylt/Rømø Bight in Germany. A significant dependence between the erosion shear stress and the benthic diatom chlorophyll *a* concentration in the uppermost 1 mm layer was found for the muddy areas. This dependence decreases with decreasing grain-size fraction <63 µm. For stations with low phytobenthic coverage a weak dependence of erosion shear stress on grain-size fraction <63 µm was found.

Using optical techniques two main classes can be distinguished from ground based measured high resolution reflectance spectra. The first class contains information on the sediments type i.e. grain-size fraction <63 µm. The second class corresponds to the phytobenthos which can be subdivided into benthic diatoms and other phytobenthic species. A significant correlation was found between reflectance spectra and grain-size fraction <63 µm and also between reflectance spectra and the benthic diatom chlorophyll *a* concentration. So the erodibility of tidal flats can be mapped with optical remote sensing when the benthic chlorophyll *a* concentration and sediment grain-size fraction <63 µm are used for estimation of the erosion shear stress. Optical measurements and erosion shear stress measurements and their relationships are discussed.

Kurzfassung

[HAKVOORT, J. H. M. & HEINEKE, M. & HEYMANN, K. & KÜHL, H. & RIETHMÜLLER, R. & WITTE, G. (1998): Optical remote sensing of microphytobenthic biomass: a method to monitor tidal flat erodibility. – Senckenbergiana marit., **29** (1/6): 77–85, 9 Abb., 1 Tab.; Frankfurt a. M.]

In mehrjährigen Feldversuchen wurden Grundlagen für ein Monitoring kritischer Schubspannungen von Wattflächen mittels optischer Fernerkundung entwickelt. Die Messungen wurden in zwei Bereichen des Nordfrieschen Wattenmeeres, der Sylt-Rømø Bucht und der Meldorfer Bucht bei Büsum, durchgeführt. Für Schlickwatten zeigen die kritischen Schubspannungen eine deutliche Abhängigkeit von der Chlorophylla Konzentration benthischer Diatomeen an der Oberfläche. Diese Abhängigkeit wird mit abnehmen-

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dem Feinkornanteil der Sedimente schwächer. An Stellen mit geringer Bedeckung durch Diatomeen zeigt sich eine schwache Abhängigkeit der kritischen Schubspannung vom Feinkornanteil <63 µm der obersten Sedimentschicht.

Reflexionsspektren von Wattoberflächen mit unterschiedlicher Bedeckung von Phytobenthos wurden mit hoher Wellenlängenauflösung aufgezeichnet. Zwei Klassen von Spektren lassen sich dabei unterscheiden. Die erste Klasse enthält als Information den Feinkornanteil <63 µm der Wattoberflächen für bewuchsfreie Bereiche. Die zweite Klasse ist dem Phytobenthos zugeordnet und kann anhand klarer Spektralsignaturen in Mikrophytobenthos und weitere Makrophyten unterteilt werden. Zwischen den Reflexionsspektren und dem Feinkornanteil sowie der Chlorophyll-a Konzentration des Mirkophytobenthos bestehen signifikante Korrelationen.

Eine Kartierung kritischer Schubspannungen aus optischer Fernerkundung über den Feinkornanteil und die Chlorophyll-a Konzentration des Mikrophytobenthos ist daher möglich. Die Messungen der kritischen Schubspannungen und Reflexionsspektren werden im einzelnen diskutiert sowie funktionale Zusammenhänge hergeleitet.

Introduction

The stability of the tidal flats is one of the most critical issues for the development of the Wadden Sea. Recent studies in the East Frisian (Flemming & Nyandwi 1994) and North Frisian Wadden Sea (Higelke 1996; Bayerl et al. 1996; Reise et al. 1997) indicated a depletion of fine-grained surface sediments together with a net loss of sediments and tidal flat areas over the last decades. A continuation of these processes may degrade the Wadden Sea's ability to act as a large-scale wave breaker and also affect the benthic species compositions and abundance and the benthic primary productivity. A mapping of the changes in sediment stability, erosion shear stress, on a broad range of scales may help to monitor anthropogenic impact on the tidal flats. Here optical remote sensing can be a useful tool.

In the absence of biogenic influences the erodibility of sediments depends on the grain-size distribution as the predominant controlling parameter (Yalin 1977). Williamson & Ockenden (1996) showed consistency between data from muddy and sandy sites when the erosion shear stress is considered as a function of dry density. The microphytobenthos increases the resistance of sediment surfaces against tidal currents and waves (Holland et al. 1974; Coles 1979; Grant et al. 1986). Particularly, benthic diatoms form a tough network of Extracellular Polymeric Substances (EPS) which stabilises the sediment by trapping the particles (Führböter 1983; de Jonge & van den Berg 1987; Paterson et al. 1994; Yallop et al. 1994). Additionally, the EPS reduce the current induced shear stress by smoothing the surface. Yet, clear relationships between chlorophyll *a* concentration as a measure of microbial biomass and erosion shear stress are still lacking. The sometimes inconclusive and contradictory results indicate a multifunctional dependence of erosion shear stress and show the need of large data sets sufficient to disentangle the contributions of the main determinant factors. An overview on this issue is given by Paterson (1994).

The initial part of our investigations deals with ranking the importance of the biological, chemical and physical factors which may influence the erodibility of undisturbed tidal flat sediments. Quantitative relationships between the erosion shear stress and its main determinant parameters are established. The possibility to determine sediment types <63 µm by optical remote sensing was already demonstrated (Kleeberg 1990; Yates et al. 1993) using information of the Thematic Mapper sensor onboard of the LANDSAT satellites. For mapping the erosion shear stress also a relationship has to be found between reflectance spectra and chlorophyll a concentration of microphytobenthos. If the optical information is significantly related to the biomass and also a significant relationship exists between the erosion shear stress and phytobenthos coverage and sediment grain size, it should be feasible to design a map of the erosion sensitivity of the tidal flats using optical remote sensing.

This paper presents first results from combined field measurements of erosion shear stress, bio-geochemical parameters and optical reflectance of tidal flat surfaces. The measurements covered a representative range of sediment types and phytobenthic assemblage. These investigations are part of the SEAPOCS (Sediment Erosion, Algal Pigments and their Optical Characteristics) project established at the GKSS Research Centre.

Material and Methods

Study Sites

For the present study two intertidal flats in the German Bight, the Sylt-Rømø Bight and the Meldorfer Bight near Büsum were selected (Fig. 1). The choice of these sites was based on former research which showed that together they covered the complete range of sediment types from mud to sand (Austen 1994; Gast et al. 1984). Also the representative assemblages of the microphytobenthos (Asmus & Bauerfeind 1994) and significant stands of macrophytobenthic species were covered (Reise & Lackschewitz 1997; Asmus et al. 1997). The microphytobenthos was dominated by diatoms. The dominant species of macrophytes included the seagrasses *Zostera marina* and *Zostera noltii*, the green algae assemblage of *Enteromorpha/Cladophora/Ulva* spp. and the brown algae *Fucus vesiculosis*.

For the erosion measurements the Sylt-Rømø Bight was sampled at spring and late summer in the years of 1992 to

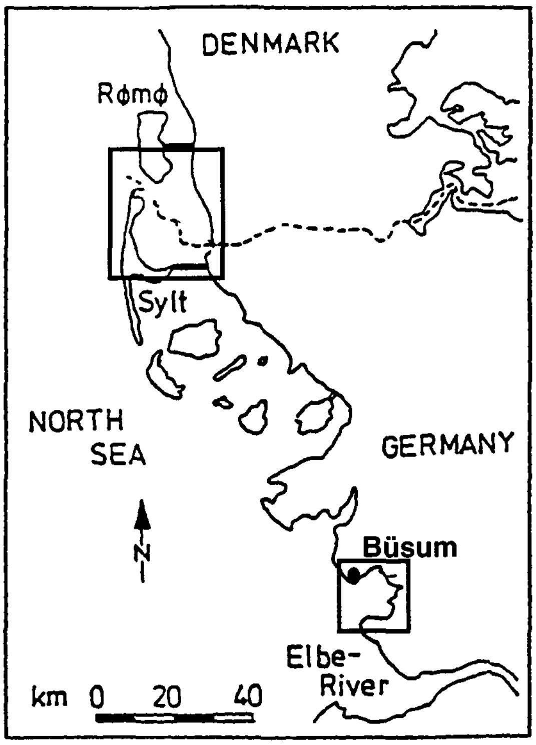

Fig. 1. Map of the North Frisian Wadden showing the experimental sites of the Sylt-Rømø Bight and the Meldorfer Bight close to the city of Büsum.

1995 as a part of the research project SWAP (Reise et al. 1996, 1997). In situ optical measurements were obtained during the spring and late summer of 1996 at both sites.

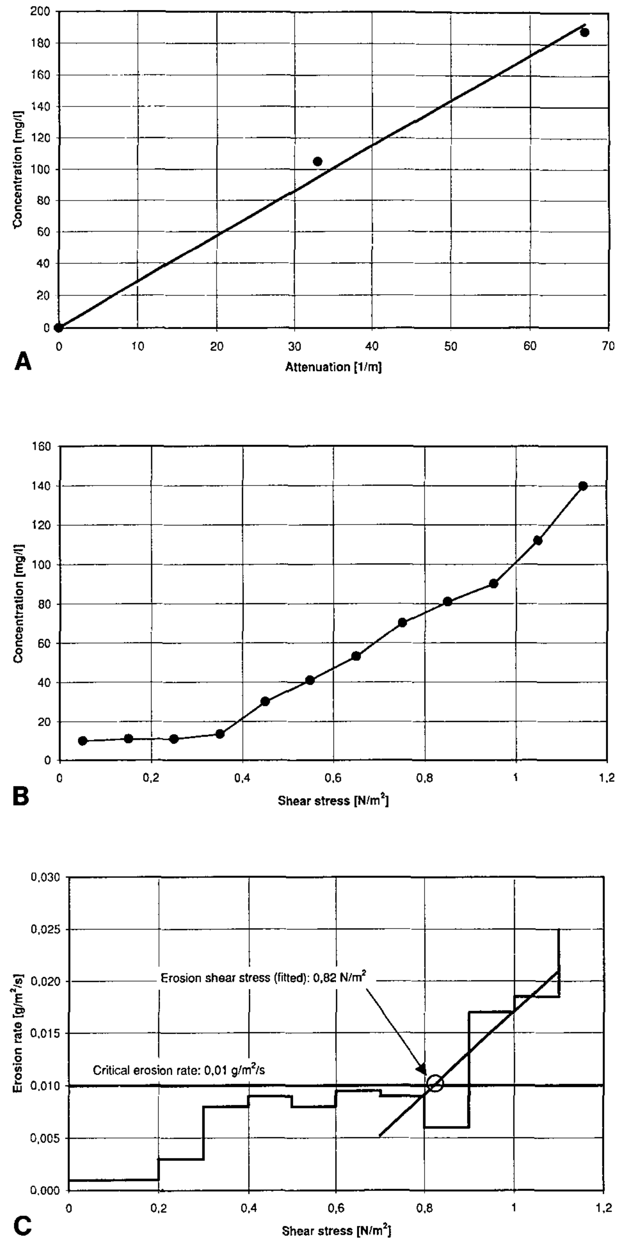

Fig. 2. Experimental curves of one of the erosion experiments to demonstrate the procedure to determine the erosion shear stress. – (A) Calibration curve relating the attenuation coefficient of the transmission readings to the suspended sediment concentration in the perspex tube. (B) Suspended sediment concentration versus the applied shear stress. (C) Erosion rate versus applied shear stress. – To determine the erosion shear stress a linear function is fitted to the data in the region around the second significant increase of the erosion rate (denoted by the crosses). For further details see text.

Erosion Measurements

The sediment cores were sampled on the tidal flat, with 10 cm diameter perspex tubes. Sampling time was always about one hour after the sampling position were free of water. Immediately after, they were transported to a closed by laboratory. The EROMES device (Schünemann & Kühl 1993; Cornelisse et al. 1994; Witte & Kühl 1996) was used to determine the erosion shear stress. Turbulence and hence the erosion is induced by a propeller above the sediment surface. The applied shear stress was calibrated by means of quartz sands with known critical shear stress. For these investigations, the shear stress was increased by 0.1 N/m^2 every 5 minutes. This ensured an almost constant erosion rate at the end of each shear stress interval. The present upper limit of the applied shear stress is 3.0 N/m^2 for the EROMES device. The average erosion rate for each shear stress interval is calculated by the time derivative of the measured suspended matter concentration. Therefore sandy samples with a fine-grain fraction <63 µm of less than 5% were not taken into consideration. As an example for the evaluation procedure, the three diagrams of Fig. 2 show the individual concentration calibration curve (a), the concentration as a function of the applied shear stress (b) and the fit of the erosion rate for the determination of the erosion shear stress (c). This fit requires a detailed study of the erosion rate progress during the experiment because in the most cases there are two distinct shear stress values where the erosion rate increases significantly. The first value indicates erosion of unconsolidated fine-grained material deposited on the surface during low tide and differs from sample to sample. The amount of this resuspended material is controlled by the wave and current conditions (de Jonge & van Beusekom 1995). The second value is the real erosion shear stress of the

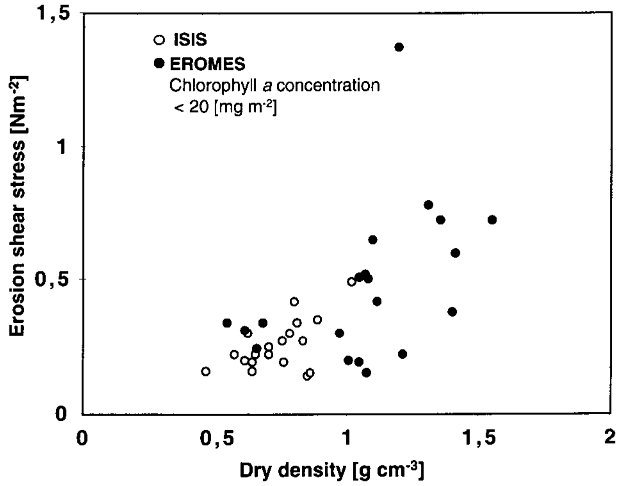

Fig. 3. Erosion shear stress versus dry density of the sediment surface. – The EROMES data are limited to chlorophyll a concentrations <20 mg/m² in the surface to minimize biogenic influence. – ISIS data are adapted from WILLIAMSON & OCKENDEN (1996).

consolidated bottom and this value is generally used in our investigations.

The EROMES results fit favourably into the ISIS data (WILLIAMSON & OCKENDEN 1996) for the considered abiotic cohesive sediments which are simply characterised by their dry density (Fig. 3).

Optical Measurements

Reflectance spectra with a 4 nm resolution were simultaneously measured in the optical window 420–780 nm at different detection angles simultaneously using a modified CCD-based Portable Multi-Channel Spectrometer (Spectral Signatures, Dublin, Ireland). The modification was necessary on the fibre optic connectors to the spectrometer to stabilise the optical pathway. Light collected by optical fibres is fed into the spectrometer and dispersed across the horizontal array of the CCD. The input fibres are stacked vertically at the entrance to the spectrometer thus producing high resolution reflectance spectra along the vertical array of the CCD. Dark currents (i.e. the instruments background) also are measured simultaneously and subtracted from the measured light signal. For the present work five optical fibres were employed. They had a 20° angle of view and were mounted into a frame at a height of 2 m height above the sediment surface. One fibre was directed downwards towards a reference reflectance panel thus collecting the incident light spectrum L_d. The other four were directed towards the tidal flat surface thus measuring the reflected light spectrum L_u. One of these L_u fibres collected light arriving perpendicular from the sediment surface and the other three collected light from an angle of 30° zenith and variable azimuth angle with 90° interval. The detected sediment surface was some 0.7 m². Typical signal integration times used for the present work were in the order of five minutes. The reflectance spectra were calculated by L_u/L_d.

Bio-geo-chemical Measurements

The uppermost 1 mm layer of the sediment surface which had been optically measured of the optical measured area was sampled. For comparison with the optical measurements the hole detected area was sampled. For comparison with the erosion measurements the samples were taken close to the sediment cores. The samples were well mixed and sub- samples were taken to measure the pigment pigments concentration of the microphytobenthos, the amount of the grain-size fraction <63 µm, the water content, the hydrocarbon content, and the amount of the total and particulate organic matter present-fraction. The pigment concentrations were measured using the acetone extraction and reverse-phase column HPLC technique of (WRIGHT et al. (1991). The grain-size fraction was determined by wet sieving with mesh-size 63 µm (DIN 4188 1977). The water content of the sediment was determined by drying to constant weight for 24 hours drying at a temperature of 105°C. For the determination of hydrocarbons the phenol-sulphuric acid method of LIU et al. (1972) was used. The total organic matter fraction was measured by loss of ignition (DIN 18128 1990) after the samples had been oven-dried at a temperature of were put into a oven at 550°C for 1 hour. The particulate organic carbon was measured by means of the infrared absorption of the combustion gases after the converting process at high temperature.

Results

Erosion Measurements

In order to disentangle the influences of the different parameters on the erosion shear stress, a stepwise analysis of the erosion data was applied. In the analysis, all samples with a complete set of erosion and bio-geochemical parameters were considered, in total 73. First, the complete data set was subjected to a factor analysis. This calculation resulted in two factors (see Tab. 1) which divide the measured parameters in two distinctive groups: to the first factor all parameters describing the physical characteristics and the measured biological sum parameters contribute. Chlorophyll *a* concentration and erosion shear stress contribute exclusively to the second factor. However, no distinct correlation was found between the chlorophyll *a* concentration and the erosion shear stress. Clear dependencies of erosion shear stress on chlorophyll *a* concentration can be observed when the data are subdivided by fine-grain fraction into four sediment classes after FIGGE et al. (1980): sand and sandy mud (fine-grain fraction 0–25%), muddy sand (fine-grain fraction 25–50%), mud (fine-grain fraction 50–85%), and clayed mud (fine-grain fraction >85%) (see Fig. 4).

In mud and clayed mud erosion shear stress increases strongly with chlorophyll *a* concentration. With decreasing mud content this dependence becomes weaker. For sand and sandy mud no correlation was found.

Table 1. Factor analysis of the measured bio-geochemical parameters and the erosionshear stress.

	Factor loads	
	1	2
Dry density	0.97	0.08
Water content	-0.96	0.06
Porosity	-0.91	0.05
Carbohydrates	-0.90	0.01
POC	-0.89	-0.12
Fine-grain fraction <63µm	-0.88	-0.14
Wet density	0.88	0.14
Chlorophyll *a*	**0.02**	**0.87**
Erosion shear stress	**0.07**	**0.85**

To study exclusive dependencies on physical parameters, all samples with a chlorophyll *a* concentration below 20 mg/m^2 were examined separately. They show a slight decrease of erosion shear stress with increase of fine-grain fraction <63 µm (Fig. 5).

Optical Measurements

The measured reflectance spectra of the different surface types have very distinctive signatures (Fig. 6). Two main classes of spectra can be distinguished. The first class of spectra

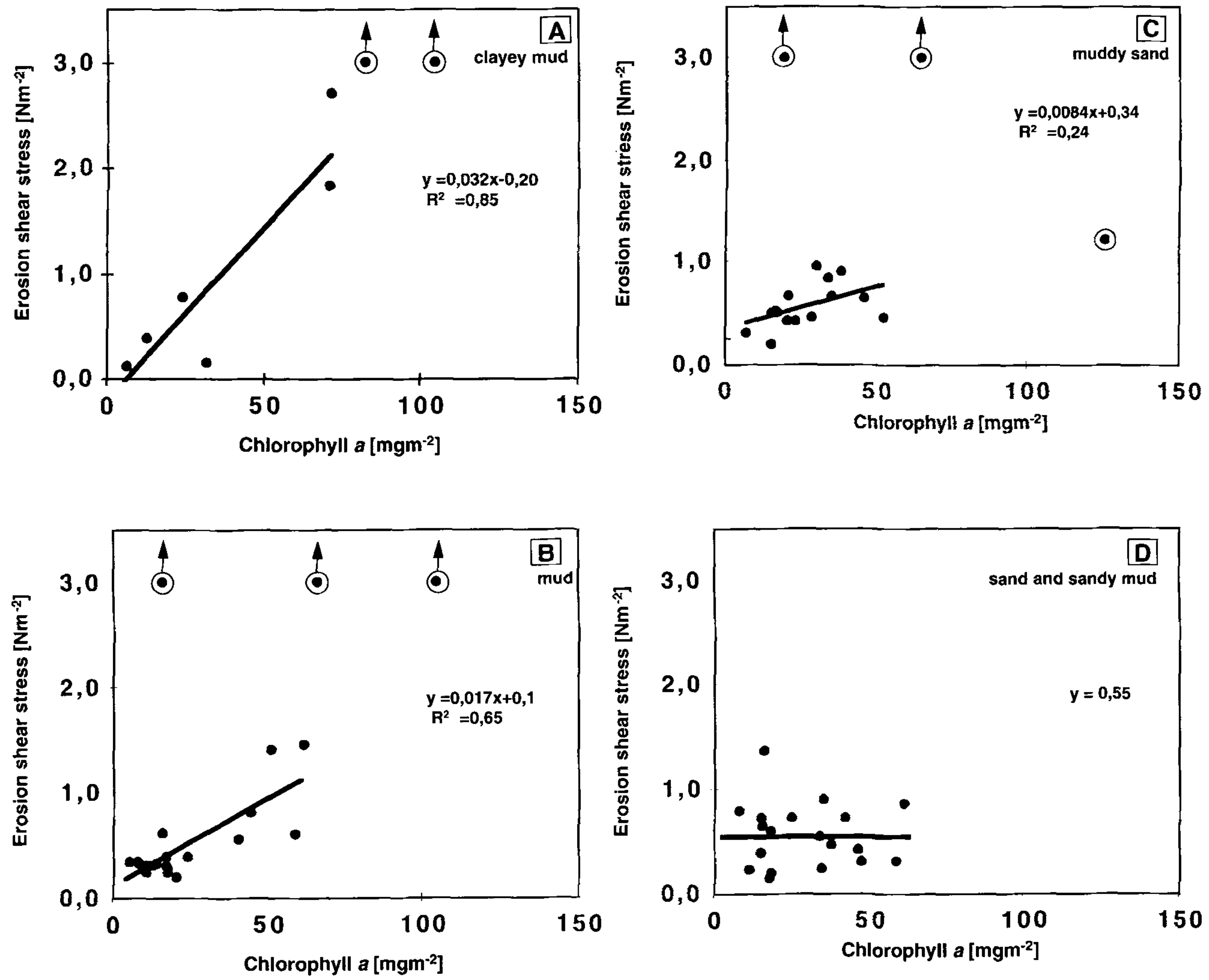

Fig. 4. Erosion shear stress versus chlorophyll *a* concentration in the surface of purely diatom covered sites. –The lines in (A)–(C) are fitted linear functions. In (D), a constant value was fitted to the data.

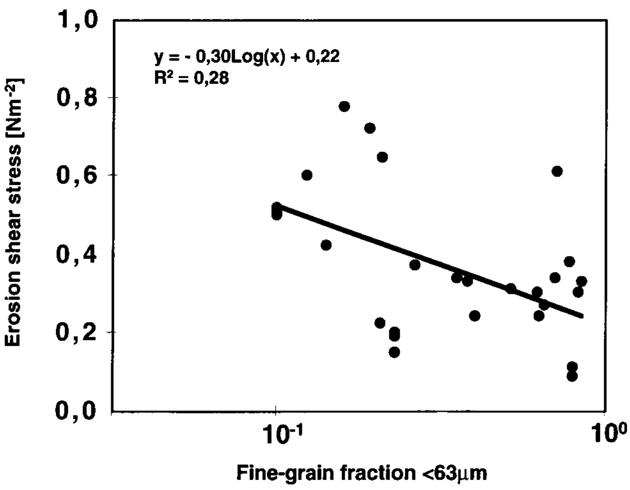

Fig. 5. Erosion shear stress versus the logarithm of the grain-size fraction <63 µm of the sediment surfaces. – Included are only data with chlorophyll a concentrations <20 mg/m² in the surface to minimize biogenic influence. The line is the fitted linear function.

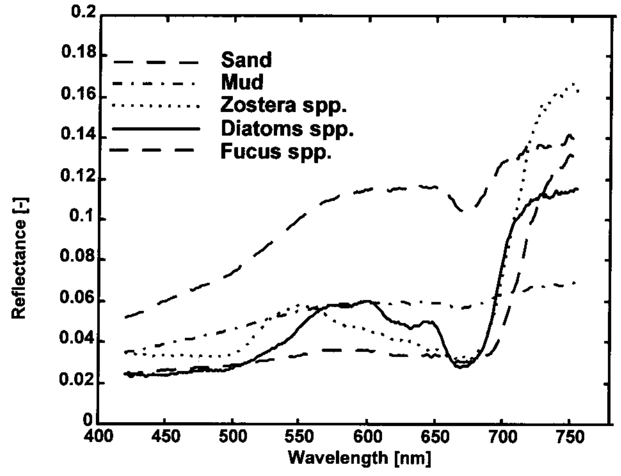

Fig. 6. Typical reflectance spectra of two uncovered sediment types and of some phytobenthic species.

contains information on the surface sediment type (Class I spectra). These spectra are characterised by a gradual increase in the reflectance increased with increasing wavelength. The slope of each individual thespectrum contains information on the amount of the grain-size fraction <63 µm. Sandy areas can be distinguished from muddy sediment types by having a steeper slope, due to the fact that sandy sediments have a higher reflectance in the near-infrared region. Irrespective of sediment type, however, all spectra showed a drop in the reflectance around 670 nm due to the absorption by chlorophyll *a* which seems to be always is present on these tidal flats. The second class of reflectance spectra corresponds to the phytobenthos (Class II spectra). These can be characterised by the high reflectance in the near- infrared region (around 750 nm) and a low reflectance in the red region (670 nm).

The initial class separation between sediment and phytobenthic types is based on the ratio of the logarithmic reflectance logR(750)/logR(670) where the numbers in brackets are the wavelength in nm. A ratio greater than 0.92 for a given spectrum is considered as an almost pure sediment signal, whereas a ratio value less than 0.92 means that the dominant surface signal originates from plant material. In case of coverage by diatoms this means a concentration of chlorophyll *a* greater than 20 mg/m² (Fig. 7). Using these unique spectral signatures of surface types it is possible to distinguish the different plants: (a) diatoms, (b) brown algae *Fucus vesiculosis* and (c) seagrasses *Zostera marina* and *Z. noltii* and green macroalgae, *Enteromorpha* spp. *Cladophora* spp. and *Ulva* spp. The separation logic is displayed in Fig. 8.

From the Class I spectra it is possible to estimate the amount of the fine-grain fraction present using the ratio logR(750)/logR(420) (Fig. 9). These wavelengths were chosen since here the effects due to absorption by accessory plant pigments are minimal. The concentration of chlorophyll *a* in the upper 1 mm of sediment also shows a good correlation with that Class II diatom reflectance spectra using the ratio logR(750)/logR(670) (Fig. 7). The only exception was found for a sandy area in the Königshafen, a small basin within the Sylt-Rømø Bight.

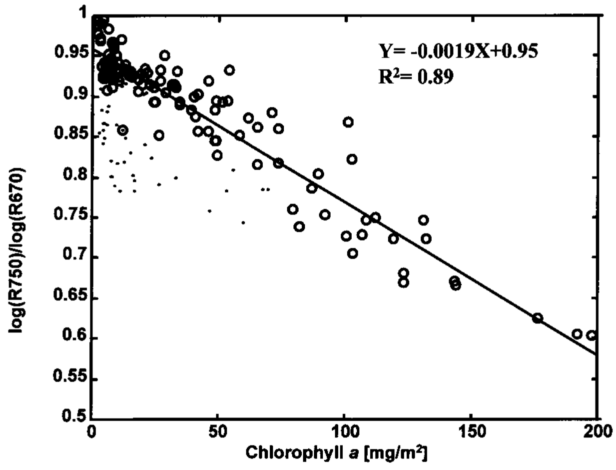

Fig. 7. Relationship between the concentration of chlorophyll *a* in the surface and the ratio of the logarithms of the reflectance at 670 nm and 750 nm. – The points indicate measurements from stations in a sandy area having a large grain size and low organic matter content. They were not included in the fit.

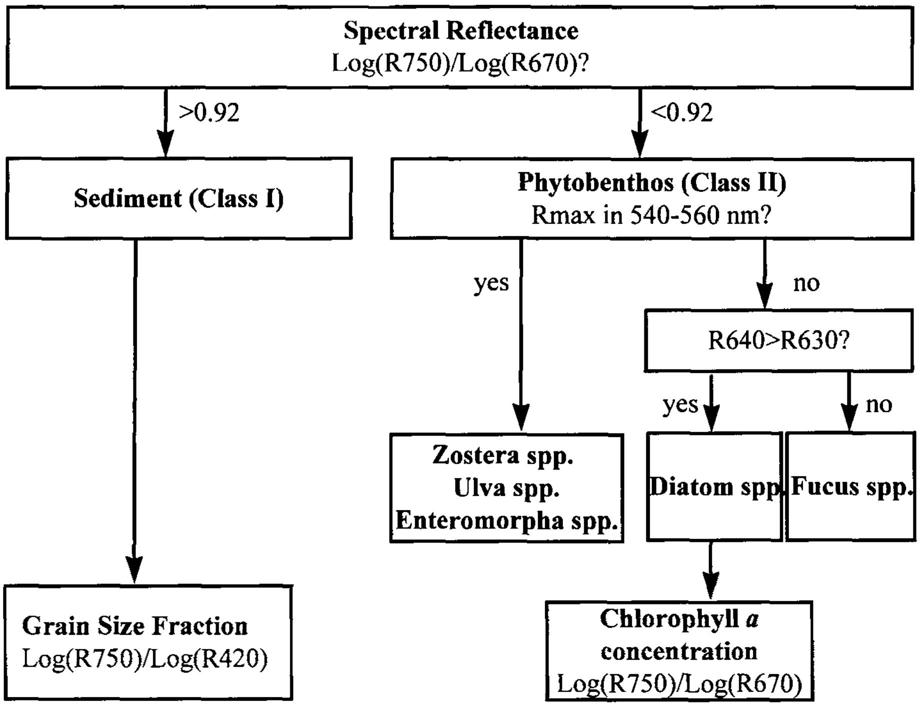

Fig. 8. Procedure for the identification of sediment type and phytobenthic surface types on a tidal flat. – Rmax means the maximal reflectance in the range from 500 to 660 nm.

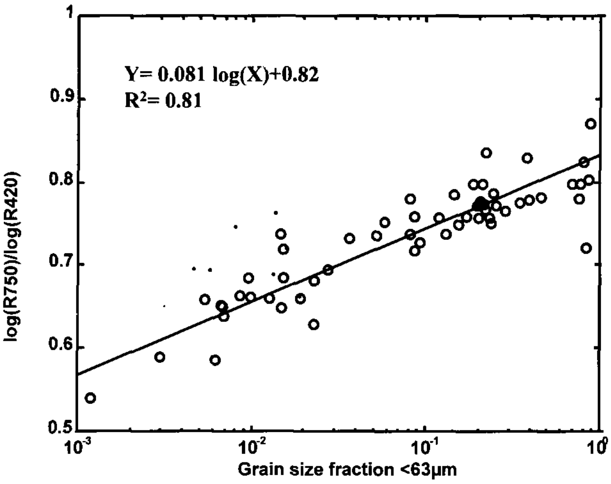

Fig. 9. Relationship between the grain-size fraction <63 μm in the sediment surface and the ratio of the logarithms of the reflectance at 420 nm and 750 nm. – Only sediments with a chlorophyll a concentration of <20 mg/m² in the surface were used.

Discussion

The results indicate, that the erosion shear stress of Wadden Sea tidal flats depends mainly on two factors: the chlorophyll a concentration and the fine-grain fraction (<63 μm) on the sediment surface. These parameters also have a significant relationship to the reflectance spectra. So a basis has been established to map erosion shear stress using optical remote sensing.

To relate the erosion shear stress to the optical signal for diatom covered areas, the dependencies of erosion shear stress on chlorophyll a concentration were approximated by linear function fits for clayed mud, mud and muddy sand. For sand and sandy mud, a constant value was assumed. Excluded from the fit are the data with erosion shear stress above 3.0 N/m², since these represent those measurements limited by the present EROMES device. For chlorophyll *a* concentrations below 20 mg/m² these are regarded as outliners for statistical reasons although we can only speculate about their particular causes. The high pigment concentration data point in Fig. 4c has been excluded from the fit, too, since it otherwise would dominate the result. The functional relationship between erosion shear stress and the logarithm of the fine-grain fraction for low biogenic influence was also assumed as a linear function (Fig. 5).

The resulting functions with their associated parameters are shown in Figs. 4–5. They have to be considered as first approximations for a number of reasons. Only few measurements have been performed at sites with higher pigment concentrations, so the definition range of the functions has to be restricted to chlorophyll *a* concentrations below 60 mg/m^2. In some of the figures (Figs. 4c–d, 5) the statistical significance of the fits are weak due to the scatter of the data. Furthermore, since the EROMES device does not allow any measurements on erosion shear stress above 3.0 N/m^2, it remains open whether a linear relationship still exists at higher pigment concentrations.

To improve the statistical significance of the above functional relations more erosion data are needed. An extension of the EROMES device to measure shear stresses above 3,0 N/m^2 is in preparation. Particularly, the chlorophyll *a* range above 60 mg/m^2 has to be explored for all sediment types. The selection of the sampling positions may be guided by optical remote sensing using the transfer functions (1)–(5). To investigate more thoroughly the dependencies for low biogenic influences campaigns at winter time are planned.

The present research created a statistically robust library of reflectance spectra of the most important surface types. It consists of the spectral signatures of uncovered sediment and of the different phytobenthic species. Also the dependence of the spectral reflectance on the angular distribution of the incident light will be included. Under a fully overcast sky the reflectance measured from the sediment surface is different compared to that measured under a clear sky. The footprint of airborne or spaceborne imaging spectroscopy may include a mixture of plant species and sediment types resulting in a composed reflectance spectrum. Procedures have to be developed to calculate the contributions of the different plant species to the total bottom coverage. This problem is going to be worked on in the near future.

Combining the relationships of the erosion and optical measurements to chlorophyll *a* concentration and fine-grain fraction in the surface layer, resp., yields the following transfer functions of tidal flat reflectance R(λ) with λ being the wavelength in nm to erosion shear stress t_{ero}:

a) low biogenic influence (chlorophyll *a* concentration <20 mg/m^2)

$$t_{ero}\ [\mathrm{N/m^2}] = -3.7 \times \log R(750)/\log R(420) + 3.3 \qquad (1)$$

b) diatom dominated influence (chlorophyll *a* concentration 20 mg/m^2–60 mg/m^2)

for clayed mud

$$t_{ero}\ [\mathrm{N/m^2}] = -17.0 \times \log R(750)/\log R(670) + 16.0 \qquad (2)$$

for mud

$$t_{ero}\ [\mathrm{N/m^2}] = -8.9 \times \log R(750)/\log R(670) + 8{,}7 \qquad (3)$$

for muddy sand

$$t_{ero}\ [\mathrm{N/m^2}] = -4.4 \times \log R(750)/\log R(670) + 4.6 \qquad (4)$$

for sand and sandy mud

$$t_{ero}\ [\mathrm{N/m^2}] = 0.55 \qquad (5)$$

The values of the parameters have to be considered as first approximations due to the arguments given in the previous paragraph for the erosion results. The error of these formulas is dominated by the erosion measurements; therefore, the R^2 values of the fits in Figs. 4–5 are also valid for the transfer functions (1)–(5). It is expected that further erosion measurements will lead to significant refinements of the results.

Fine-grain fraction and chlorophyll *a* concentration cannot be measured at the same time by optical methods. To map erosion shear stress by optical remote sensing fine-grain fraction and microphytobenthos distribution have to be detected at different times. It is best to map the fine-grain fraction shortly after the period of spring storms is over and before the first diatom bloom. Under the assumption that from this moment the horizontal distribution of surface sediments remains constant until winter this distribution can be used to select the appropriate algorithm to derive erosion shear stress from the reflectance spectra.

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