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ORIGINAL PAPER

Seagrass recovery in the Northern Wadden Sea?

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Abstract Aerial surveys on seagrass (*Zostera* spp.) indicate a three to fourfold increase in bed area from 1994 to 2006 with up to 100 km^2 or 11% of intertidal flats in the Northfrisian Wadden Sea (coastal eastern North Sea), observed at seasonal maximum in August when flying during low tide exposure 300 to 500 m above ground. When viewed from the air, difficulties in distinguishing between seagrass and green algae and a lack of contrast on dark-coloured mudflats are sources of error in areal estimates. Particularly the positioning of beds remote from shores was imprecise. However, the consistency in method over time gives confidence to the inferred positive trend which is opposite to the global pattern. Both, the spatial pattern and a recent decrease in storminess suggest that sediment stability is the key factor for seagrass dynamics in this tidal area. On exposed sand flats, high sediment mobility may be limiting and along the sheltered mainland shore land claim activities with high accretion rates may cause a scarcity of seagrass. The potential area of seagrass beds may be twice as large as the realized maximum in 2006 but eventually the rising sea level will reverse the observed seagrass expansion.

Keywords Aerial survey · Green algae · Intertidal · Land claim · Sediment stability · *Zostera*

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Introduction

Seagrasses are a functional group of flowering plants with limnic ancestors which colonized coastal oceans (Short et al. 2007). In the North Sea they occur with two species of the eelgrass genus *Zostera* (den Hartog 1970). Important ecosystem functions in the North Sea are that (1) beds of seagrass provide shallow water habitats for a diversity of organisms including a nursery for fish, (2) waterfowl feed on eelgrass but quantitatively the contribution to the detrital food web prevails, and (3) beds of seagrass with associated organisms constitute an effective filter for nutrients and trap particulate matter (Asmus and Asmus 2000; Nacken and Reise 2000; Polte et al. 2005). Furthermore, persistent seagrass beds are considered excellent indicators of ecosystem health because they reflect temporally integrated environmental conditions and are rather easy to assess (Borum et al. 2004).

In the northern Wadden Sea, which is a coastal part of the eastern North Sea with extensive intertidal mud and sand flats, meadows occur mostly in the upper to mid tidal zone. From June to September meadows give a conspicuous dark shade when viewed from the air. Beds often exhibit a topography of hummocks and runnels where *Z. noltii* is more tolerant to desiccation and gives rise to hummocks while *Zostera marina* prefers puddles and runnels (den Hartog 1971). In the intertidal zone of the Wadden Sea, *Z. marina* is mostly an annual and *Z. noltii* mostly a perennial plant.

Historically, *Z. marina* was growing in the shallow subtidal and lower to mid intertidal, while *Z. noltii* occurred in the mid to upper intertidal near the island of Sylt in the northern Wadden Sea (Nienburg 1927). A wasting disease in the 1930 wiped out the subtidal *Z. marina* (Wohlenberg 1935) and it never came back while intertidally both species survived (Reise et al. 1989). The same happened in the southern Wadden Sea (Harmsen 1936) but there also the intertidal beds of eelgrass declined since the second half of the last century (de Jonge et al. 1993, Kastler and Michaelis 1999). Experimental studies suggested that coastal nutrient over-supply may have been a major cause of the decline in the intertidal (e.g. Philippart 1995; van Katwijk et al. 1997, 1999).

As part of the Trilateral Monitoring and Assessment Program (TMAP) of the Wadden Sea, we started in 1994 with regular aerial surveys to assess seagrass occurrence in the northern Wadden Sea in an attempt to test whether the decline observed in the south will extend to the north. Instead, we found the largest seagrass area of the Wadden Sea gradually increasing over the years. Although an aerial survey alone cannot reveal the causes of observed patterns, we discuss whether the recent trend may constitute a recovery and use our observational data to make novel suggestions for research.

Methods

Surveying followed a simple procedure. With a Cessna type of airplane we were flying in an meander-like course at heights between 300 to 500 m across an area of 80 × 30 km with 930 km^2 of intertidal sediment flats as potential seagrass area. This area is located between Eiderstedt peninsula, the northern tip of the island of Sylt and the Danish-German border, and is called the Northfrisian Wadden Sea. Flying time was 2–3 h around low tide period which is shifting from southwest to northeast with a maximum lag of 2 h. Flights were performed each year in June, July and August/September to keep track of seasonal development. Together with an experienced pilot, four observers were on board and three of them were taking notes on maps 1:100,000 making decisions on position and identity of dark shading: seagrass, green algal mats or both mixed. In case of uncertainty, questionable darkish to greenish areas were flown over twice or more and looked at from various angles and heights to reach consensus. We assume that seagrass beds with <20% coverage are not included in this aerial survey. This assumption is based on ground truth experience from selected sites. Recognized boundaries of seagrass beds varied with contrast between seagrass and sediment color, presence of algae and visibility of the day. Decisions were supported by ground truth knowledge from almost all sites visited at least once over the last three decades, and from aerial surveys in previous months of the same year. After landing, a synthesis was prepared on the basis of three individual maps obtained from each flight and transferred into a vector based geographical information system. Geometries are stored as coordinates in the Gauss-Krueger system of the third longitudinal zone. In the area under investigation this system has a high accuracy (spatial error <1%) allowing the direct use for spatial statistics. Data from August/September 1994–2006 were superimposed to identify persistent beds and to estimate the total area where seagrass had been growing in that period.

Results

A recurrent pattern of seagrass beds getting denser and larger from June to August is apparent (Fig. 1). From August onwards, shed leaves were accumulating at high tide wash lines and the coverage in the meadows began to decline. Subsequent records refer to August/September as the approximate seasonal maximum.

To obtain an overview, observations from 13 consecutive years have been superimposed (Fig. 2). An area of 187 km^2 or ~20% of intertidal flats was found with seagrass including beds observed only once. More frequent occurrences of seagrass with observations in >4 years were found on 54.5 km^2 (5.8% of intertidal flats), and of these highly persistent beds observed in >8 years covered 22.5 km^2 (2.4% of intertidal flats). Only 12.0% of the total seagrass area consisted of permanent or almost permanent beds.

At first sight, the spatial pattern may seem haphazard. However, more intertidal area is covered within 3 km distance of island shores (excluding exposed beaches on the western shores of barrier islands) than of the mainland shore, with 43 versus 25 ha km^{-1} of shoreline respectively. Tidal flats without seagrass are often areas of the lower shore further off the islands or the upper shore along the mainland. Furthermore, tidal flats exposed to a long fetch

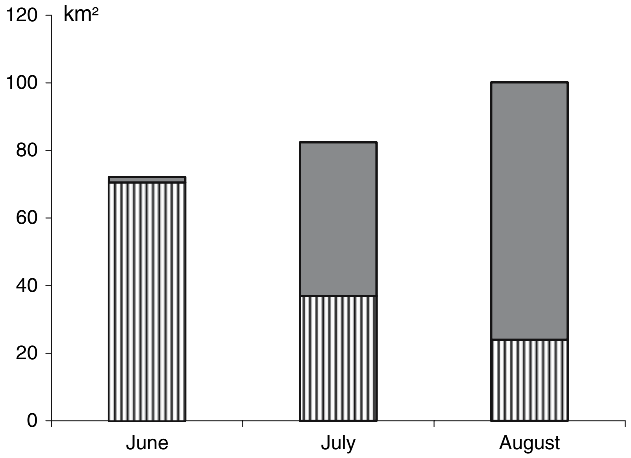

Fig. 1 Seagrass beds with low (20–50%, *hatched*) and high (>50% coverage, *shaded*) from June to August 2006 in the Northfrisian Wadden Sea

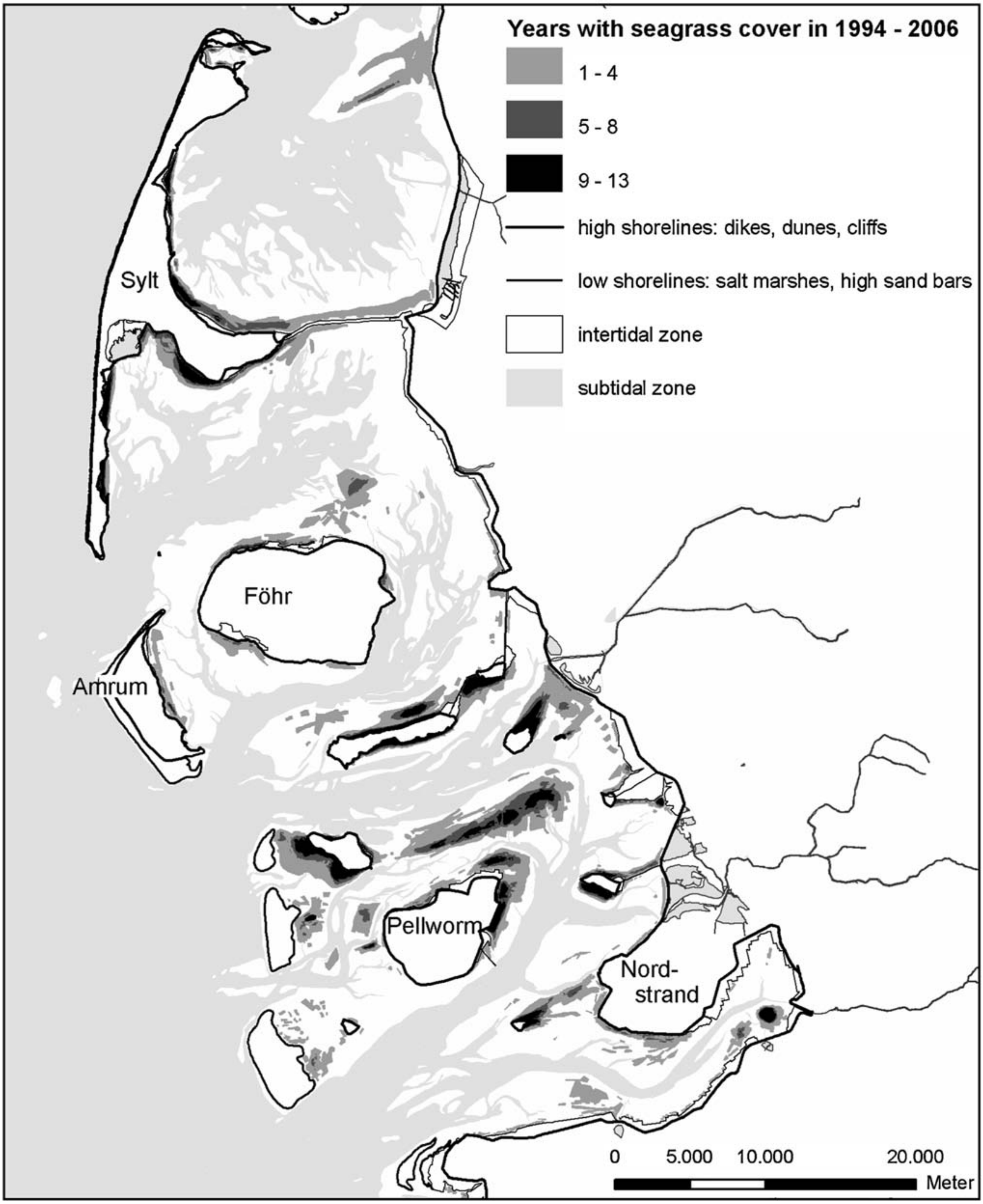

Fig. 2 Occurrence of seagrass (*Zostera noltii* and *Z. marina*) in the intertidal zone of the Northfrisian Wadden Sea in August/September 1994–2006. Intensity of shading refers to the number of years seagrass has been observed. Beds with <20% coverage are not included (see "Methods")

from southwest to west are often with no or few seagrass beds.

The timeline of area covered by seagrass shows a significant positive trend from 1994 to 2006 ($y = 15.9 + 5.2x$, $r^2 = 0.8$, $P < 0.05$), with a notable increase over the last 6 years (Fig. 3). Mean area covered over this period was 52 ± 22 km^2, the smallest area covered was in 1994 with 31.7 km^2, and the largest was in the last year with 100.2 km^2. In addition to the 13 consecutive years, area estimates obtained with the same method for 1978 and 1991 are included in Fig. 3, both falling within the range of 1994–2006. The survey in 1991 was met with difficulties because at that time green algal mats attained peak coverage, were mixed with seagrass and confounded the estimate. Furthermore, a ground truth survey in 1992 covering about half of the region (Bock and Brodowski 1993) revealed large areas with scattered growth of *Z. marina*, indicating an expansion phase of this species. This was not observed in 1978 and was rare in the later period. *Z. noltii* has been by far the dominating species in terms of area occupied in the period 1994 to 2006 (pers. communication by A. Schanz, M. Loebl and own obs.).

Discussion

The Wadden Sea of the Dutch, German and Danish North Sea coast comprises the largest coherent zone of tidal flats in the world, famous for its huge flocks of migratory birds feeding there at low tide. Only in the northern part of the Wadden Sea, the seagrass habitat still takes a large share of the intertidal (Reise et al. 2005). Any significant change in seagrass cover will have effects on the entire ecosystem and may be used as an indicator for the ecological quality of the coastal waters. Therefore it is important to discuss the reliability of the long-term observations presented here, to interpret the spatial and temporal patterns and—if possible—to anticipate future developments of seagrass area.

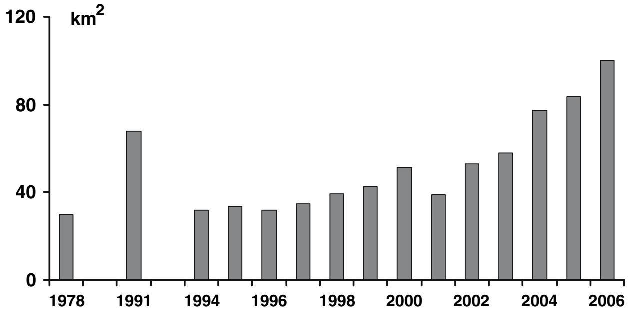

Fig. 3 Area (km^2) of seagrass beds (>20% coverage) recorded by aerial surveys in the Northfrisian Wadden Sea in August 1978, 1991 and 1994 to 2006

How reliable are aerial surveys?

Mapping seagrass by flying across tidal flats during low tide exposure is a rough but the only feasible rapid-assessment method when areal size is as large as the Northfrisian Wadden Sea with seagrass beds scattered throughout. Observers need experience before reproducible results can be achieved, and the first author participated in all flights to secure continuity in the method. In spite of that, there are three main causes of error when mapping seagrass from the air:

Error of identification

Seagrass beds appeared to be darker than ambient unvegetated flats but the possible confusion with green algal mats and a lack of contrast with dark and muddy sediments confounded seagrass mapping. In addition to dark shading, texture provided a cue. Intertidal seagrass beds often but not always generate a hummock structure with small runnels in between while green algal mats appear to be more homogeneous. At a low coverage, green algae were composed of elongated patches oriented in current direction, while patches of seagrass are either circular or irregular in shape. Color is highly variable because of sunlight effects, water cover and epiphytes on seagrass, and is therefore of little help in identification. Where green algae covered seagrass entirely, areas were not mapped as seagrass beds, although the seagrass underneath may have been still alive. Of course, it was not possible to separate the two species of *Zostera* from the air.

Error of area

Based on ground truth experience we estimate that the visible boundary of a seagrass bed looked at from 300 to 500 m altitude corresponded roughly to 20% coverage by seagrass at low tide exposure. However, this varies with the contrast between seagrass and sediment color and with the presence of algae. The latter were often more abundant at seagrass bed margins than in central parts. This is likely to give rise to incorrect decisions on bed boundaries.

Error of location

Seagrass beds occurring close to shore could be better located than seagrass beds further away from shores due to the availability of topographic cues. Varying water levels caused the low tide line and the course of gullies to be less useful for orientation. However, in the Northfrisian Wadden Sea most seagrass beds occur close to shore. Twenty islands and high sandy shoals and also mussel beds helped in positioning seagrass beds correctly.

The errors mentioned above sum up to underestimate persistence of individual seagrass beds. Since coverage less than about 20% is not detectable from the air, persistence at a lower density has been missed. Therefore, the estimated 12% of seagrass area occupied over at least two thirds of the period of investigation is a minimum figure. Nevertheless, the large area where seagrass was observed only over up to one third of the period indicates a highly dynamic state of seagrass populations in the area. Within intervals of ~7 years, Frederiksen et al. (2004a, b) also observed considerable areal changes (39–62%) of *Z. marina* in shallow Danish waters based on aerial photographs. An analysis of a set of aerial photographs of the North Frisian Wadden Sea available for August 2005 came up with an area estimate similar to the flight observations (+12%; Poszig et al., in prep.). However, the interpretation of aerial photographs was not independent from the other aerial surveys and from ground truth knowledge. Aerial photographs can eliminate the error of incorrect positioning but otherwise are subject to the same problems of identifying and delimiting seagrass area, and take more time and costs. Satellite images cannot account for the tidal time lag within the area, and require a cloud-free sky at low tide which is rarely met. In conclusion, we recommend to continue with the rapid-assessment of seagrass area by means of direct flight observations.

What causes the spatial pattern?

We hypothesize that a key factor in the occurrence of seagrass beds in the study area is sediment stability. The spatial pattern of seagrass beds in the northern Wadden Sea as shown in Fig. 2 may be explained by (1) sediment mobility too high for seagrass to occur on sandy flats exposed to a long fetch from the prevailing southwesterly and westerly winds, (2) islands and high sands providing shelter against wave disturbances originating from that direction, (3) clay from former salt marshes underlying soft tidal sediments and facilitating sediment stability and firm rooting, and (4) sediment accretion rates being too high for seagrass in the nearshore zone along the mainland coast. To confirm this, a field survey on sediment dynamics needs to be conducted. An emphasis on sediment stability shall not reject other factors often discussed for seagrass distribution such as sediment type, tidal level, hydrodynamics, light availability, salinity, nutrient over-supply and herbivory. However, for the spatial pattern in the northern Wadden Sea these other factors or any combination of them do not seem to provide a consistent cue to the observed pattern.

Cabaço and Santos (2007) conducted short-term burial and erosion experiments with *Z. noltii* which is lacking a vertical rhizome. They found negative effects on shoot density even when the sediment level was altered by a few centimeter only. A similar sensitivity was found for *Z. marina* by Mills and Fonseca (2003). Incidences of wave erosion have been observed to expose roots and rhizomes. Such patterns occur on a small scale (10 to 100 m) at moving ridges of sand (Cunha et al. 2005, own obs.), and may also apply to the scale of entire tidal flats (km) with an unbalanced sediment budget or with a high internal sediment mobility. A rather stable sediment surface layer seems to be a pivotal condition.

Sandy flats of the lower tidal zone exposed to waves with a long fetch from the prevailing wind directions may be too dynamic for seagrass to become established. In a model calculation, Philippart et al. (1992) found *Z. marina* and *Z. noltii* to be equally sensitive to sediment instability. Patch dynamics of *Z. marina* have been attributed to sediment movement (Harlin and Thorne-Miller 1982). Attempts to restore *Z. marina* beds in the southern Wadden Sea failed in exposed areas lacking sufficient shelter (Bos and van Katwijk 2007; van Katwijk 2003). Van Katwijk and Hermus (2000) stabilized sediments artificially with shell fragments. This facilitated survival of transplanted *Z. marina* at exposed but not at sheltered locations. Usually the source of sediment instability is wave exposure or high current velocity which in addition are known to have direct adverse effects on seagrass (Fonseca and Bell 1998; Schanz and Asmus 2003; van Katwijk and Wijgergangs 2004).

Although in the northern Wadden Sea most seagrass beds occur in the leeward shelter of islands and high sands, not all fit into that pattern (Fig. 2). Deviations can be explained by layers of dense clay underneath the sediment surface. These are remnants of former salt marshes. All of the marshy islands were once larger and hence are surrounded by remnant clay layers at variable depth below the sediment surface (e.g. Bantelmann 1966; Plath 1943). This also applies to the largest seagrass bed found in the study area which occurs north of the island of Pellworm ("Pellwormer Plate"). Clay layers and occasionally also layers of compressed peat may not only keep away lugworms but also provide a firm rooting (Fig. 4).

Philippart (1994) conducted transplant experiments at such a site. *Z. noltii* that grew above a layer of clay was not capable to grow outside a clay area. In the presence of the bioturbating lugworm *Arenicola marina* it did not persist. Conversely, lugworms did not settle above the clay because of an insufficient depth of soft sediment for burrowing. Exclusion of lugworms also may facilitate seagrass colonization. On lugworm exclusion plots (Volkenborn et al. 2007), patches of *Z. noltii* began to show up after 5 years in significantly higher numbers than on control plots where bioturbating lugworms remained present (N. Volkenborn, pers. comm.).

Dense patches of *Z. noltii* and *Z. marina* tend to trap particles and generate hummocks (Bos et al. 2007). A surplus supply of deposits may soon exceed what can be tolerated.

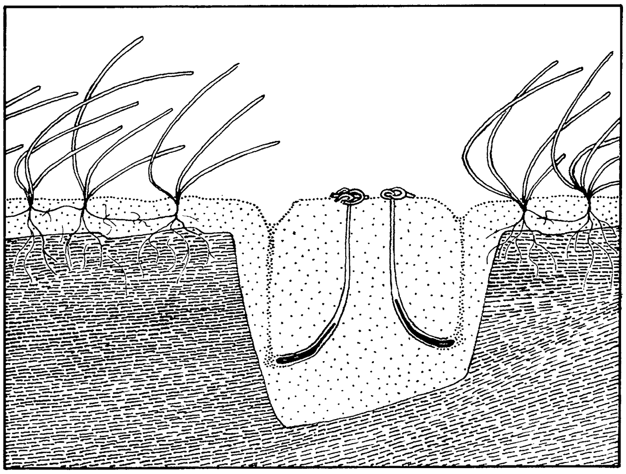

Fig. 4 Firm clay of drunken medieval marshland superimposed by marine sediments. Former drainage ditch provides sufficient sediment depth for *Arenicola marina*. By bioturbation the lugworm inhibits the seagrass *Zostera noltii*. Schematic from observations at Hallig Hooge, Nordstrandischmoor and Pellworm (see text)

Along the mainland shore, most salt marshes were found to extend seaward between 1988 and 2001 (Stock et al. 2005). This indicates a rising of nearshore flats, almost always enforced by rectangular grids of brushwood groins. These are permeable fences made of brushwood wedged between parallel rows of wooden poles. They are employed to enhance deposition. The ultimate aim is to gain saltmarsh area in front of dikes in order to dissipate storm surge wave energy. Sedimentation rates of 100 to 400 mm have been achieved within 3 years (Erchinger et al. 1996). Such land claim activities along the mainland shore exceed the ability of *Z. noltii* to cope with burial. This may explain the relative scarcity of seagrass in front of the mainland as shown in Fig. 2.

Land reclamation fields with brushwood groins are subjected to recurrent excavation of drainage ditches. This is lethal to seagrass. Groins also tend to trap green drift algae. These accumulate and then suffocate the seagrass underneath (Reise and Siebert 1994; Bos and van Katwijk 2007).

Why a positive trend?

On a world-wide scale seagrass beds are declining due to increased human pressure in the form of (1) nutrient loading mainly at developed coasts in the temperate zone, (2) siltation linked to coastal deforestation mainly in the tropics, and (3) various mechanical disturbances such as dredging (Hemminga and Duarte 2000; den Hartog and Phillips 2001; Green and Short 2003; Burkholder et al. 2007). The positive seagrass development observed in the northern Wadden Sea is opposite to the global trend. Also in the southern Wadden Sea a former decline (de Jonge et al. 1993; Kastler and Michaelis 1999) seems to have come to a halt (Reise et al. 2005). We here argue that the main cause for the increasing trend in seagrass area in the northern Wadden Sea has been a decrease in storminess since 1995 which entails a decrease in sediment mobility.

Although still far above pre-industrial level, riverine nutrient loadings have been decreasing over the last two decades (van Beusekom et al. 2005, this volume). Experiments have shown direct and indirect negative effects of reactive nitrogen on *Z. noltii* and *Z. marina* (Philippart 1995; van Katwijk et al. 1997, 1999; Burkholder et al. 2007). The level of eutrophication is higher in the southern than in the northern Wadden Sea (van Beusekom 2006). Thus, one would not expect a synchronous response of seagrass throughout the entire region as it seems to be the case. Massive green algal mats are believed to have been triggered by eutrophication (Fletcher 1996). They peaked in the intertidal German Wadden Sea in the early 1990s, since then declined, fluctuated from year to year but did not cease altogether (Reise and Siebert 1994; Kolbe et al. 1995; van Beusekom et al. 2005). Green algal mats are capable of extinguishing beds of seagrass by suffocation (den Hartog 1994; Cardoso et al. 2004) but at the scale of the entire Northfrisian Wadden Sea no inverse relation of green algal area and seagrass area is apparent (own unpubl. data).

Schanz et al. (2002) suggested a synergistic effect of eutrophication and hydrodynamics. Experiments showed that massive fouling by microalgae on seagrass leaves could only be prevented by grazers such as the snail *Hydrobia ulvae* under calm conditions. With increasing current velocity grazers failed to control fouling and fouling may have been facilitated by an ample supply of nutrients. Hydrodynamics also directly affect density and shoot morphology of *Z. noltii* (Schanz and Asmus 2003). These experimental studies support the idea that changes in wave pattern and storm surge frequency could be responsible for the observed areal increase in seagrass beds over the last decade. Decreasing mechanical disturbances such as bivalve dredging or bottom trawling (Marencic 2005) may not have caused the seagrass expansion. Such disturbances are local and their recession cannot account for a recovery of seagrass throughout the Wadden Sea.

A regionally consistent trend in seagrass areal development may be better explained by a decrease in storm surge levels since the mid 1990s which has been indicated by Weisse and Plüß (2006). Considering winter periods (November–March) in the German Bight, an increase in storm activity since the 1960s with highest levels around 1990–1995 was followed by a decrease. Storm surge water levels in summer (April–October) showed a slight decrease over the entire period. It needs to be experimentally investigated whether storm related sediment instability in winter is relevant for subsequent seagrass development. If true, we have to predict that an anomalous storm frequency observed November–December 2006 will have a negative effect on seagrass bed area in 2007. This supposition would be in line with the pivotal role of sediment stability in explaining the spatial pattern of seagrass beds.

May seagrass continue to expand?

Not knowing for sure what has caused the recent positive trend in seagrass area, it is obviously impossible to make a prediction. Further, it is not clear whether the expansion of seagrass area over a couple of years is part of a decadal fluctuation or the beginning of a recovery. The latter rests on the assumption that the occurrence of *Zostera* spp. all over the tidal zone and in patches into the upper subtidal as observed eighty years ago by Nienburg (1927) and Harmsen (1936) resembles a pristine condition which could return once human pressures have relaxed.

Intermittent area extensions of annual *Z. marina* beds in the intertidal zone has been repeatedly observed (Reise et al. 1989, 2005; Bock and Brodowski 1993). However, the positive trend over the last decade is a gradual expansion by perennial *Z. noltii* and thus may constitute a long-term recovery.

If lack of sediment stability is indeed the most important limiting factor, then seagrass beds could still expand beyond the maximum cover observed in 2006. At least the entire area shaded in Fig. 2 might be regarded as potential seagrass area which is almost twice the extent of 2006. Of course, this may never be realized and only holds if climatic forcing does not entail a decrease in sediment stability by increasing water levels at the Northfrisian coast. Extrapolating winter storm surge levels observed at tide gauges over the last four decades (Weisse and Plüß 2006) into the next 40 years, would raise water levels by about half a meter, irrespective of any acceleration in global sea level rise. In the long run such a development would be disadvantageous for intertidal seagrass beds because a fixed dikeline precludes areal adjustments. Increased land claim activities by means of brushwood groins to enhance saltmarsh progression would be at the expense of potential seagrass area.

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