Colonisation of Spartina on a tidal water divide, Danish Wadden Sea

Niels Vinther, Christian Christiansen & Jesper Bartholdy

Abstract

The spread of Spartina on a tidal water divide has been followed in subsequent aerial photos. Spartina first appeared in the area in 1964, it spread rapidly to 1976. From 1976 to 1988 a significant die-back is observed. This die-back was more than recovered in 1995. Apart from the tidal range, no single physical factor (number of storm surges, rise in mean sea level, temperature) in itself appears to account for the spread. The die-back period had a number of cold winters, which points to the role of ice in the Spartina die-back. Spartina may establish at levels of +0.16 m DNN. Coherent Spartina vegetation cover is observed at +0.30 to +0.40 m DNN on the tidal water divide. In comparison with the local tidal range, possible future planting of Spartina in salt marsh management strategies should take place at levels, which are inundated no more than 5 hours per tidal cycle.

Keywords

Spartina, die-back, salt marsh, sediment accretion.

Niels Vinther, e-mail: nv@geogr.ku.dk
Christian Christiansen, e-mail: cc@geogr.ku.dk
Jesper Bartholdy, e-mail: jb@geogr.ku.dk

Institute of Geography, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark.

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During the spring of 1931 Spartina was planted in the Danish tidal area of Ho Bugt as a land reclamation plant and to protect the coastal zone from erosion. Both Spartina anglica and Spartina x townsendii were planted (Pedersen, 1974); in the following no distinction between the species will be made. Half of the plants had died (drowned) by the following summer because they were planted at too low levels on the intertidal flat, while the rest disappeared during the following winter due to the physical action of ice (Jørgensen, 1934).

Succeedingly, Spartina was planted at higher levels on the intertidal flats in the following years. Spartina is widespread in the area today, although there have been problems establishing the plants in some parts of the bay. These problems are probably caused by the physical actions of waves and ice (Meesenburg, 1972).

In general, the livlihood of Spartina has long been known to be limited by a number of factors, most of which depend on the water level fluctuations. The most important water level variations in this context are produced by the tide. Tidal inundation alters porewater content (Mendelssohn & Seneca, 1980) and aeration (Armstrong et al., 1985) in the substratum, as well as light intensity and duration (Hubbard, 1969) and salinity (Ranwell et al., 1964) in the covering water column. Degree of flooding strongly influences possible wave action too (Groenendijk, 1986). Additionally, seasonal changes in water levels and wind effects may also play a role. Longer periods without inundation of the intertidal flats partly allows flushing of seeds with fresh water from precipitation, which is necessary for germination, and they also allow new plants to become anchored in the sediments (Boorman, 1999).

The purpose of the present paper is to study which environmental physical factors influence the spread of Spartina at geographical latitudes, which is considered marginal for its survival (Ranwell, 1967). Knowledge of the creation of new salt marsh areas and of the spread of already-planted Spartina may have increasing importance in salt marsh management strategies as traditional threats such as man's activity in the coastal zone become augmented by the new threats from predicted sea level rise (Boorman, 1999; Christiansen et al., 2000).

Study Area

The study area (Figure 1) is in the Grådyb tidal area and is sheltered from the North Sea by the Skallingen barrier spit. The area has an average tidal range of 1.5 m (1.3 m at neap, 1.7 m at spring). Meteorologically induced sea level variations are much stronger and sea levels may reach 4.4 m above DNN (Danish Ordnance Datum) during storm surges (Aagaard et al., 1995). Easterly winds cause a lowering of the sea level. Mean sea level in the area has risen by an average rate of 1.3 mm/year since the first tide gauge was established in Denmark in 1888. This long-term trend is strongly influenced by a recent sea level rise, as the last 25 years have experienced a sea level rise of 4.2 mm/year (Christiansen et al., 2000). Thus, the mean sea level is approximately 0.15 m DNN (Nielsen & Nielsen, 2000). The current speed in Store Løb (Figure 1) may reach 1.2 m/s whereas on the tidal flats the maximum current speed does not exceed 0.35 m/s. Sedimentation on the Skallingen salt marsh is variable in both time and space. However, the average long-term accretion rate is 2-3 mm/year. In the pioneer zone with Spartina vegetation, the rate is as high as 8 mm/year (Nielsen & Nielsen, 2000). Thus, yearly accretion rates by far exceed long term mean sea level rise.

About 85% of the fine-grained sediment deposited in the Grådyb tidal area is estimated to be imported from the North Sea (Bartholdy & Madsen, 1985). Import of material from the North Sea to the Wadden Sea is suggested to take place during storm surges (Jakobsen, 1961). New evidence, however, suggests that strong import is restricted to windy episodes following long periods of low energy conditions in the North Sea. During such low energy periods fine-grained material may settle to the bottom and thereby act as a reservoir for import to the Wadden Sea area when resuspended during high-energy episodes (Bartholdy & Anthony, 1998).

The vegetation is dominated by *Spartina townsendii and Salicornia maritima* in the new low-lying salt marsh areas of Skallingen;
by *Puccinellia maritima and Suaéda maritima* at intermediate levels and by *Halimione por-tulacoides*, *Limonium vulgare*, *Aster tripolium*, *Plantago maritima* and *Artemisia maritima* at the highest levels.

Morphological evolution at Skallingen and its surrounding areas is described in Aagaard et al. (1995) and will not be further analysed in the present paper. However, it is mentioned that Nyeng was presumably connected to Langli by salt marshes before the "Great man killer" storm surge of 1634 (Aagaard et al., 1995).

The present study was undertaken on the approximately 3 km long tidal divide between Hobo Dyb and Hjerting Løb (Figure 1). The tidal flat is sandy with a mean grain size of approximately 200 μm (Sørensen, 2000), though presently the vegetation collects fine-grained sediment, transported advectively to the area from the North Sea and from the northern parts of Ho Bugt. The width of the Spartina zone is about 200 meters near Nyeng Hale.

The main focus is on the newly established salt marsh, Nymarsk, in the area east of Nyeng Hale. The area around Nyeng is a natural environment without noticeable human influence, excepting remnants of groynes on the northern shore of Nyeng Hale.

Spartina and the environment

Spartina can only establish on intertidal flats when these have reached a level at which they are only covered by the tide for about 3 hours per tidal cycle (Van Duin et al., 1996). As the tidal range in the study area is 1.5 m, Spartina will occur at levels of +0.30 to +0.40 m DNN. However, Spartina is observed at levels as low as +0.16 m DNN. By camparison, the lower limit of Spartina in the southern part of the Danish Wadden Sea area with a larger tidal range is +0.40 to +0.60 m (Møller, 1963).

Once established, the pioneer zone with Spartina comprises greater sedimentation than both the intertidal flats in

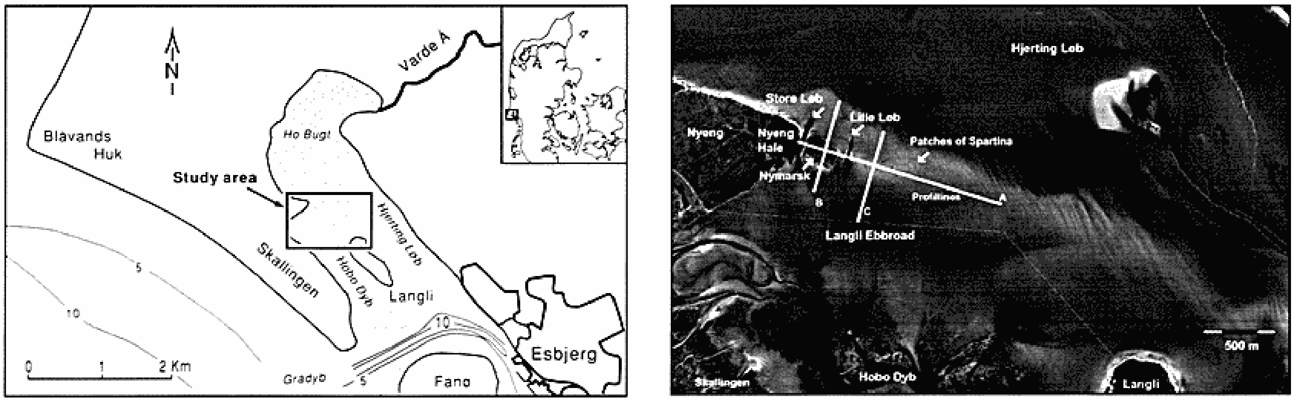

Figure 1: Study area. The background photograph is taken in 1995. The inserted section is a map of Denmark and Skallingen with surroundings.

front of Spartina areas (Christiansen & Kristensen, 1986) and the higher elevated and more mature salt marsh areas behind (Boorman, 1999; Nielsen & Nielsen, 2000).

Spartina areas trap fine-grained sediments and are known to be a major source of sediment heterogeneity between vegetated and non-vegetated parts of intertidal flats (Christiansen & Miller, 1983; Netto & Lana, 1997).

The patches of Spartina must attain a threshold size before accumulation takes place (Christiansen & Kristensen, 1986). Before reaching this size, erosion around the plants may occur. Bruno & Kennedy (2000) found that the patch should be more than 100 m in diameter before enough sediment can accumulate to allow less halophyte plants to immigrate the patch. One of the plants to follow Spartina in a regular succession is *Puccinellia maritime*, which in Ho Bugt is found down to a level of +0.54 to +0.58 m DNN (Iversen, 1953). When the surface rises above +0.6 m DNN, species like *Halimione portulacoides* and *Aster tripolium* can immigrate. As the cover of these new immigrants become too dense, Spartina will be ousted (Ranwell, 1964). This may be due to the fact that such species come into leaf earlier than Spartina (Allen, 2000). Nielsen and Nielsen (2000) found that there is no difference in accretion rates on the salt marsh of Skallingen, where a shift in vegetation is observed.

The hybrid form of Spartina reproduces by cloning, and therefore plants in a patch are genetically identical. Lethal environmental alterations may therefore cause large areas of Spartina to die during a short period.

Methods

The analysis is based primarily on aerial photographs from 1945, 1954, 1964, 1976, 1988 and 1995. Ortho-photographs from 1995 are geocoded to UTM co-ordinates. The aerial photographs were scanned and registered to geographical co-ordinates based on the 1995-photos. The photo-analysis extends to 1995, supplemented with field observations from autumn 1998 to spring 2000.

The area only has a few stable landmarks. Therefore, dirt-road crossings, drinking spots for cattle etc. were used for image corrections. Due to such unstable points, the residual error in the corrections of the original aerial photographs result in offsets of two to three pixels (4-8 m) depending on the quality of the photo. The precision decreases eastwards due to fewer stable points. After corrections, the borders of vegetation were digitised based on the colour contrast with the lighter tidal flats.

The tidal divide was surveyed in 1999 and 2000 to study the level of the salt marsh and patches of Spartina. Profiles were levelled with a Topcon GTS6 total-station, with shots of up to 200 metres, which gives an accuracy of ± 2 mm. When establishing bench marks, shots of less than 100 metres were used. This gives an accuracy of ± 1 mm.

The wind climate was analysed from wind observations from three local lighthouses, Vyl, Sædden Beach and Blåvand. The observations have been recalculated into energy per year.

Results and discussion

Morphological Changes

Evolution of salt marshes and Spartina

The vegetated areas can be divided into two types, one consisting of coherent vegetation (Nyeng and Nymarsk) and one where patches of Spartina grow on the tidal flat towards the east.

In 1945 there was no vegetation east of Nyeng Hale. There was a marked drainage channel (Store Løb) in the north-south direction just east of Nyeng Hale.

In 1954 vegetation east of Nyeng Hale was still absent, but Store Løb has grown in length. The length of the channel is an indirect measure of how much water passes the channel. The growth of channels also indicates that the level of the surrounding tidal surface has increased forcing more water to run in the low-lying channel (Allen, 2000).

By 1964 a large area of coherent vegetation had colonised the tidal flat east of Nyeng Hale, only separated from it by Store Løb. This area is called Nymarsk (see Figure 1 and 2). Observations in the area from 1998 show that the vegetation on Nymarsk consists of several species including *Puccinellia maritima*, *Halimione portulacoides*, *Statice limonium*, *Aster tripolium*, *Festuca rubra* and *Artemisia maritima*. Store Løb has grown in width but does not appear to have grown in length from 1954 to 1964. This may however be due to a poor quality of the 1964 aerial photograph. East of Nymarsk there is a great number of Spartina patches, located as far as approximately 1500 m east of Store Løb.

Reporting on fieldwork undertaken between 1933 and 1952, Jacobsen (1953) did not mention the existence of Spartina in his otherwise long list of species from the eastern part of Skallingen. However, Iversen (1953) wrote; '*Still the occurrence (of Spartina) on Skallingen is somewhat scattered, but it grows well in the outer salt marshes...*'. This statement is based on observations from the northern part of Skallingen (approximately one km from Nymarsk) in

August 1952. Meesenburg (1972) surveyed the growth of Spartina from 1957 to 1965 and indicated that Spartina, although established, was still in its embryonic phase.

In 1976 Nymarsk had increased in size, but the number of Spartina clones further east was almost the same as in 1964. The area of coherent vegetation has increased with more than 100 % and has grown further south-southeast. The area on the southern side of Nyeng Hale has also increased, whereas erosion took place on the northern side of Nyeng. An important change from 1964 to 1976 is that a new channel developed (Lille Løb) about 350 m east of Store Løb. Lille Løb increased rather quickly to a considerable size (Figure 2). According to findings in French & Stoddart (1992) this is undoubtedly because of the elevated Nymarsk. Furthermore there are signs of one additional channel in progress.

A die-back occured between 1976 and 1988, where Nymarsk appeared to be only slightly larger than in 1964. Despite a decrease in the vegetation the eastern limit of Spartina patches had not changed markedly. The decrease in salt marsh areas is mainly observed on the easternmost part of Nymarsk, which is the most low-lying part of the area. Despite the die-back in vegetation, channels have increased in size and number. Store Løb and Lille Løb have become wider and a new channel has been generated. The new channel is located where signs of a coming channel were already observed in 1976.

In 1995 Nymarsk has grown to an extent exceeding its size in 1976. The number of individual patches has increased too. Compared to aerial photograph from 1976, the vegetation at Nyeng is now more coherent. The patches of Spartina have increased in number though there is hardly any expansion eastwards. Newly established vegetation has primarily come up on the southern and southeastern side of Nymarsk. Store Løb has decreased slightly in width due to the formation of a point bar pointing northwards, indicating a dominant current from south to north (Vinther, 2000). Some vegetation has started to grow between the two outermost channels. Lille Løb has developed northwards more than 600 m from the tidal divide. The deepest point in the channel appears to be north of the topographical divide. In March 2000 the deepest part was situated about 150 m north of the northern border of vegetation.

The eastern limit of the individual patches of Spar tina has not changed markedly over the past 40 years. It therefore appears that the natural eastern limit was reached very quickly after establishment of Nymarsk. Feist & Simmenstad (2000) found that the episodic recruitment of new Spartina patches might depend on physical factors such as temperature, sea level and precipitation.

Change of heights

The profile along the tidal divide between Hobo Dyb and Hjerting Løb (Figure 3a) shows that the highest level of Nymarsk is up to +1.05 m DNN with an average of less than +0.8 m DNN. Nymarsk is thus still somewhat lower than the

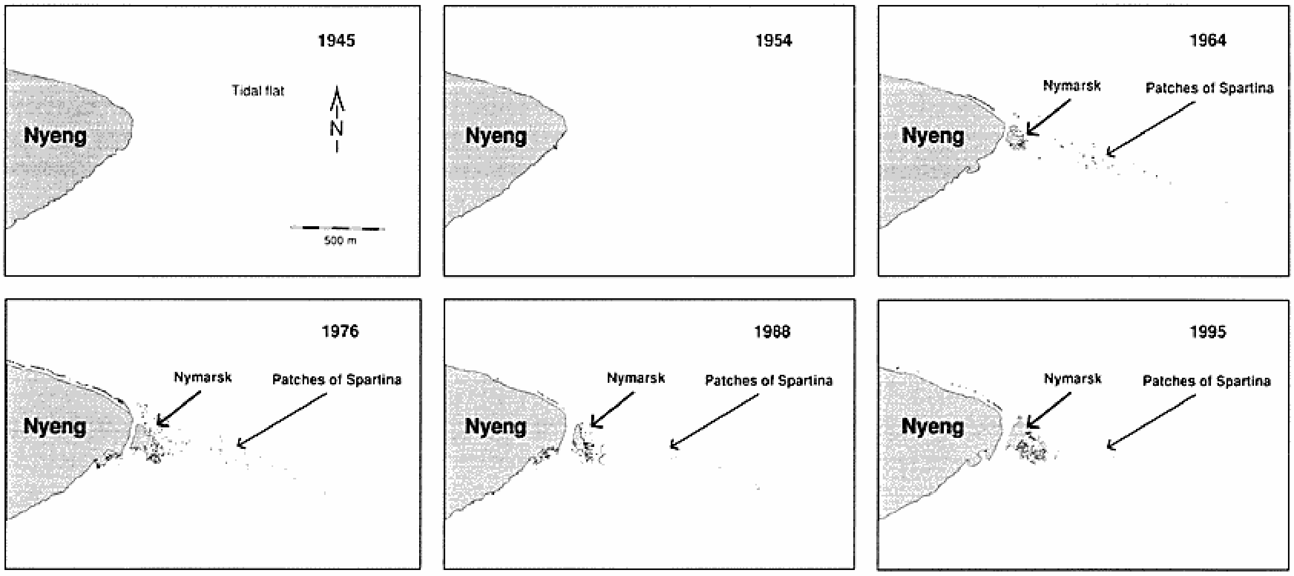

Figure 2: *Development of vegetation around Nyeng Hale, 1945 - 1995. Note the die-back between 1976 and 1988 and the almost stable eastern limit of Spartina.*

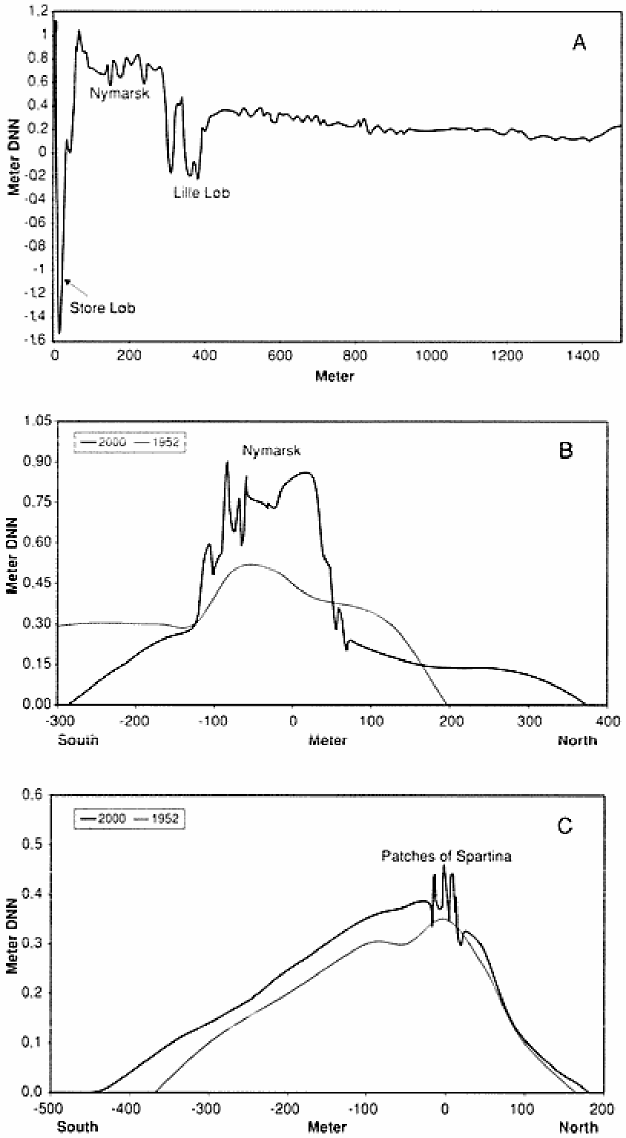

Figure 3: *Figure 3.a.b.c. Profile along the tidal divide between Hobo Dyb and Hjerting Løb (a) and two profiles across the tidal divide, 200 m (b) and 550 m (c) respectively, from Store Løb. The thin line in b and c are the surface level from 1952.*

outer salt marsh on Skallingen (Nielsen & Nielsen, 2000). The patches of Spartina start to appear between +0.16 and +0.38 m DNN. This is about 5 cm higher than the surrounding tidal flat, and duration of inundation at a level of 0.38 m DNN is approx. 5 hours per tidal cycle, which is longer than shown in studies from the Dutch Wadden Sea (Van Duin et al., 1996), but shorter than shown in studies from England (Ranwell et al., 1964). In the Danish estuary of Mariager Fjord, similar periods of inundation have been found (Christiansen & Møller, 1983). The channels are as deep as -1.5 m DNN in Store Løb and down to -0.2 m DNN in Lille Løb. The profile is located along the patches of Spartina. It was expected that the patches would be located on top of the topographical divide. However, when comparing the profiles across the tidal divide (see Figure 3c), it can be observed that the level to the south is higher than to the north of the patches. At least 100 metres south of the Spartina, the level is higher than +0.3 m. Therefore, Spartina could theoretically spread in this direction. South of Nymarsk the level quickly drops to less than +0.3 m DNN (see profile b, Figure 3), indicating that the space available for spread of Spartina is limited. Nevertheless the expansion of Spartina is towards south when looking at aerial photographs. Further east there are growth tendencies towards north despite the higher level on the southern side. Waves are ruled out as responsible for hindrance of growth, as wave height is limited to 0.10 m with winds of 10 m/s from westerly directions (Sørensen, 2000).

The tidal divide was also surveyed in 1952-1953 with an accuracy of ± 5 cm (Authorities of Esbjerg Harbour, personal com.). At that time Nymarsk was a high lying sandy tidal flat accomodating to plant growth. A comparison of these with the recent ones shows that the area close to Nymarsk has been elevated from +0.5 m DNN in 1952 to maximum +1.1 m DNN in 1999. This gives accretion rates of up to 13 mm/year. The level of the tidal flat, where the patches of Spartina are now located, has not changed markedly. It was between +0.2 and +0.3 m DNN in 1952, similar to the level in 1999 except from a minor rise in the western part close to Nymarsk. On Nymarsk there has been accumulation but towards the south erosion has taken place and the area is lowered more than 0.3 m since 1952, because Store Løb has eroded the tidal flats there. It can be concluded from the levellings that the overall level of the western part of the tidal divide has not changed markedly since 1952 except where Spartina has taken root. In August 1999 the Danish coastal authorities surveyed the tidal flat further east. This survey compared to the survey from 1952-53 shows that the level, where Spartina is absent, has lowered from +0.3 m DNN to 0.0 DNN. This lowering of the level on the tidal water divide may explain the almost constant eastern limit of Spartina.

Environmental Impacts

Nymarsk established between 1954 and 1964 and a dieback was observed between 1976 and 1988. This analysis

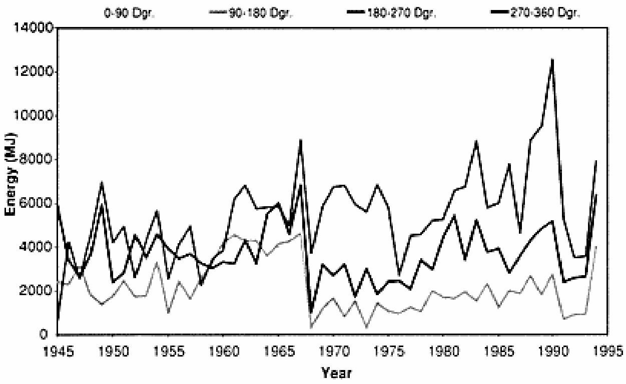

Figure 4: Wind climate change. Energy level per year from four directions. Note the high energy level from eastern directions 1960-1967 and the increasing wind from SW.

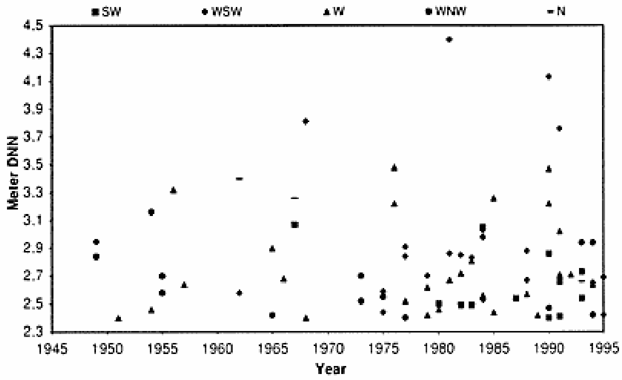

Figure 5: Storm surge changes from 1945-1994. Note the increasing number of storm surges through the period. Modified from Aagaard et al., 1995.

will focus primarily on four factors: wind climate change, storm surges, mean sea level change and ice winters.

Wind climate

Figure 4 shows the change in wind energy between 1945-1994 for four major directions. In the period 1945-60 there is an almost equal amount of wind energy from SW and NW, but after 1960 winds from SW become dominant. Further, the period 1960-1967 has a high energy level in all directions. Especially the NE and SE winds are much stronger than in the previous and following decades. During the 1990ies there is extremely high wind energy from SW.

Change in the wind energy does not appear to explain die-back of Spartina on the tidal divide because there is no marked difference in energy between the growth periods 1964-76, 1988-95 and the die-back period 1976-1988. Instead, the wind energy may play a role in the build-up of Nymarsk. Winds from SW may cause a wave induced sand transport to the tidal divide, contributing to the raise of the level of the water divide. Winds from W-NW have a smaller fetchand therefore potentially transport less sand. This argument is corroborated by the morphology suggesting that the build-up of Nymarsk is mostly pronounced towards the south.

Storm surges

Langli was connected to Skallingen before the great 1634 storm surge, indicating that storm surges can have a strong erosive effect on the vegetation in the area. On the other hand, Christiansen & Kristensen (1986) concluded that sediment was accumulated in spots of Spartina during high-energy periods. It therefore appears obvious to analyse whether storm surges have any detectable effects on Spartina in the area. A storm surge in this area is defined as water levels above 2.4 m DNN (Nielsen & Nielsen, 2000).

There has been a marked increase in storm surges since 1970 (Figure 5). Gales from a WSW-direction have especially increased as 4 storms were recorded from 1945 to 1970 compared to 18 in the period from 1970 to 1994. In the same period the total number of storm surges was 18 and 57, respectively. However, the number of storm surges cannot explain the die-back of Spartina, as there is the same number of storm surges in the die-back period between 1976 and 1988 as in the growth period from 1988 to 1994. Even the most severe storm passing Denmark in December 1999 did not seem to have had a ny negative effect on Nymarsk. Therefore, the number of storm surges is probably an insignificant factor, especially also as the number does not give information on the duration or relative strength of the storm surge.

Mean sea level variations from 1945 to 1995

The increased number of storm surges has occurred during a rise in sea level. The annual mean sea level in the period from 1945 to 1995 has a great variance from year to year, but an overall increase in water level is observed. The period can be divided into a period with hardly any sea level rise or even a slightly falling trend from 1945 to 1975/80 and a period during the last 20-25 years with a rapid rise in mean sea level, up to 4.2 mm/year (Christiansen et al., 2000). There is no clear correlation between annual mean sea level and growth or die-back of Spartina, as both die-back and growth take place during periods of rising sea level.

With the present rise in mean sea level, the rate of inundation of Nymarsk will increase. This may not cause problems for Spartina, as it is not the inundation rate alone which reduces its ability to grow (Adams & Bates, 1995). The accretion rate in the Spartina zone of the salt marsh on Skallingen has by far exceeded the rate of sea level during the last 100 years (Nielsen & Christiansen, 2000; Nielsen et al., 2000) and presently the rate of accretion in the established Spartina vegetation on the tidal water divide (15 mm/year) by far has exceeded the rate of sea level rise.

A detailed examination of the sea level variations from 1976 to 1995 was carried out to identify periods of low sea level during spring, allowing Spartina to be anchored in the sediment. There are great fluctuations during this period of time. For instance in 1981 there were periods of more than 85 consecutive hours where the tidal flat was not inundated. In other years the tidal water divide is not left uncovered for more than half a tidal cycle. However, a correlation between the water level during spring and the die-back or growth periods was not found.

Temperature

The ice cover in winter may influence Spartina negatively (Meesenburg, 1972; Christiansen & Møller, 1983). The average temperatures of the three months December, January and February were therefore examined for the period 1945-1994. Temperature data are taken from Rosenørn and Lindhart (1996).

Figure 6 shows that 7 of 11 winters in the die-back period have an average temperature below zero whereas only one, two or three winters in the expansion periods had average temperatures below zero. The wind climate during the cold periods is important as both winds and water level control the packing of ice on the tidal flats and the wind may cause physical damage to Spartina (Meesenburg, 1972). The temperature variations may be a result of the North Atlantic Oscillation (NAO) (Hurrell & Van Loon, 1997). Due to the NAO, the period 1989-1994 has been recorded as having the warmest winters in the last 50 years, perhaps even 130 years. In this period the Spartina at Nymarsk recovered rapidly. On the other hand, the winters of 1977-1979 have been recorded as the coldest (Becker & Pauly, 1996). They coincided with the die-back period of Spartina.

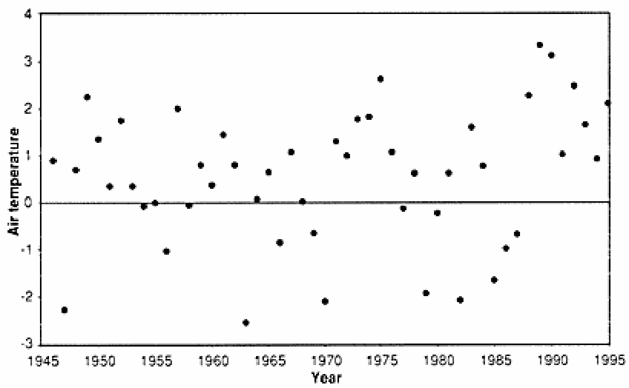

Figure 6: *Temperatures of December, January and February from 1945-1994. Note the cold period between 1977 and 1987 and the warm period in the early 1970 and 1990's. Data from Rosenørn & Lindhardt, 1996.*

Conclusions

East of Nyeng a new area of Spartina (Nymarsk) was observed in 1964. After 1964 it grew quickly in size until 1976. Between 1976 and 1988 a die-back occurred and reduced the size of Nymarsk by almost 50 %. From 1988 to 1995 Nymarsk more than recovered its 1976 size. The eastward spread of Spartina patches is limited by wave induced erosion. Wind statistics indicate that this erosion is a result of wind climate change from westerly to southwesterly winds.

An accretion rate of up to 13 mm/year since 1952 is observed in the Nymarsk. The level of the tidal flat east of Nymarsk has not risen significantly except in the patches of Spartina, where a raise of 5 cm during the period is common.

Patches of Spartina are found at levels from +0.16 and +0.38 m DNN. Coherent Spartina cover occurs at +35 to +40 cm DNN. As the mean sea level presently is +0.15 m DNN, this level of the tidal water divide is generally inundated 5 hours per tidal cycle. In attempts to use Spartina in coastal zone management programs, Spartina should therefore preferably be planted at levels with less than 5 hours inundation per tidal cycle in the Danish Wadden Sea.

Wind climate, number of storm surges and mean sea level change cannot as single factors explain the spread of Spartina. Die-back of Spartina occurs in cold winters and may be explained by physical activity of ice.

Acknowledgements

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reduces its ability to grow (Adams & Bates, 1995). The accretion rate in the Spartina zone of the salt marsh on Skallingen has by far exceeded the rate of sea level during the last 100 years (Nielsen & Christiansen, 2000; Nielsen et al., 2000) and presently the rate of accretion in the established Spartina vegetation on the tidal water divide (15 mm/year) by far has exceeded the rate of sea level rise.

A detailed examination of the sea level variations from 1976 to 1995 was carried out to identify periods of low sea level during spring, allowing Spartina to be anchored in the sediment. There are great fluctuations during this period of time. For instance in 1981 there were periods of more than 85 consecutive hours where the tidal flat was not inundated. In other years the tidal water divide is not left uncovered for more than half a tidal cycle. However, a correlation between the water level during spring and the die-back or growth periods was not found.

Temperature

The ice cover in winter may influence Spartina negatively (Meesenburg, 1972; Christiansen & Møller, 1983). The average temperatures of the three months December, January and February were therefore examined for the period 1945-1994. Temperature data are taken from Rosenørn and Lindhart (1996).

Figure 6 shows that 7 of 11 winters in the die-back period have an average temperature below zero whereas only one, two or three winters in the expansion periods had average temperatures below zero. The wind climate during the cold periods is important as both winds and water level control the packing of ice on the tidal flats and the wind may cause physical damage to Spartina (Meesenburg, 1972). The temperature variations may be a result of the North Atlantic Oscillation (NAO) (Hurrell & Van Loon, 1997). Due to the NAO, the period 1989-1994 has been recorded as having the warmest winters in the last 50 years, perhaps even 130 years. In this period the Spartina at Nymarsk recovered rapidly. On the other hand, the winters of 1977-1979 have been recorded as the coldest (Becker & Pauly, 1996). They coincided with the die-back period of Spartina.

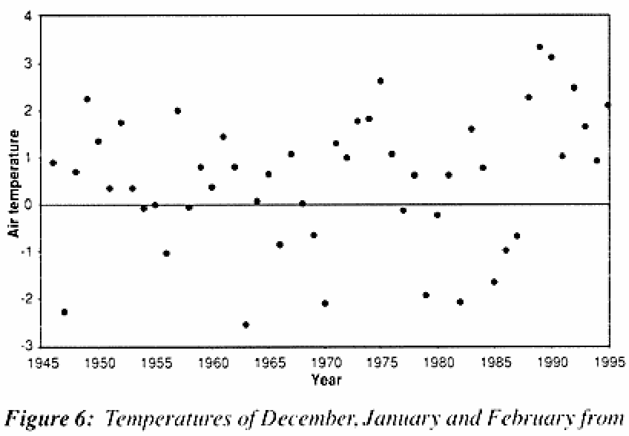

Figure 6: *Temperatures of December, January and February from 1945-1994. Note the cold period between 1977 and 1987 and the warm period in the early 1970 and 1990's. Data from Rosenørn & Lindhardt, 1996.*

Conclusions

East of Nyeng a new area of Spartina (Nymarsk) was observed in 1964. After 1964 it grew quickly in size until 1976. Between 1976 and 1988 a die-back occurred and reduced the size of Nymarsk by almost 50 %. From 1988 to 1995 Nymarsk more than recovered its 1976 size. The eastward spread of Spartina patches is limited by wave induced erosion. Wind statistics indicate that this erosion is a result of wind climate change from westerly to southwesterly winds.

An accretion rate of up to 13 mm/year since 1952 is observed in the Nymarsk. The level of the tidal flat east of Nymarsk has not risen significantly except in the patches of Spartina, where a raise of 5 cm during the period is common.

Patches of Spartina are found at levels from +0.16 and +0.38 m DNN. Coherent Spartina cover occurs at +35 to +40 cm DNN. As the mean sea level presently is +0.15 m DNN, this level of the tidal water divide is generally inundated 5 hours per tidal cycle. In attempts to use Spartina in coastal zone management programs, Spartina should therefore preferably be planted at levels with less than 5 hours inundation per tidal cycle in the Danish Wadden Sea.

Wind climate, number of storm surges and mean sea level change cannot as single factors explain the spread of Spartina. Die-back of Spartina occurs in cold winters and may be explained by physical activity of ice.

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