

#### 4. Mechanisms involved in salt-marsh rejuvenation

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#### **Abstract**

Under favourable environmental conditions, such as benign hydrodynamics, a certain base elevation, and sufficient silt availability, the capacity of *Spartina anglica* to alter the environment is crucial to set off rapid marsh formation. This small-scale ‘ecosystem engineering’ of *Spartina* induces several other processes, sometimes with large-scale consequences. First, by reducing current velocities and capturing sediment *Spartina* stimulates its growth locally. This may result in erosion along the tussock edges with strong current velocities, which inhibits lateral growth. Plus, the presence of thresholds is induced, implying that with sufficient biomass feedbacks enable *Spartina* settlement, while settlement is not possible under similar conditions with low biomass. This induces non-linear response of marsh ecosystems to changing environmental conditions, which complicates predicting the exact response to external changes.

On the scale of a complete marsh, on barrier islands sedimentation is mostly driven by the slope of the pre-marsh sand surface. During marsh growth independent, nested patterns develop superimposed on this gradient. Spatial patterning was also found in the occurrence of sand layers within the salt-marsh sediment. These indicate that salt marshes may develop under rougher conditions than previously thought, and that the contribution of washover sediment to an established salt marsh is smaller than expected.

Further we tested the applicability of natural  $\gamma$ -radiation of sediment for salt-marsh research. Identifying sources and sinks of sediment in relation to salt-marsh rejuvenation was not possible with the radiometric and corer methods, partly because the radiometric fingerprint of the fine-grained sediment seems to be homogeneous within the Dutch Wadden Sea. Measuring salt-marsh accretion with the radiometric method was only possible to a certain extent, but the method was successful in mapping grain-size variations on the intertidal flats adjacent to the salt marsh.

## **i. Problem**

Organisms changing their environment, also called ecosystem engineering, can be a potentially important process in structuring salt-marsh pioneer zones. To obtain a better insight in the formation of salt marshes on barrier islands, sedimentation processes on larger time and spatial scales were examined. Based on these results and those from the large database of soil cores, we addressed questions related to salt-marsh development. This concerns environmental conditions, sediment type and quantity, sediment sources and spatial and temporal patterns.

## **ii. Aim**

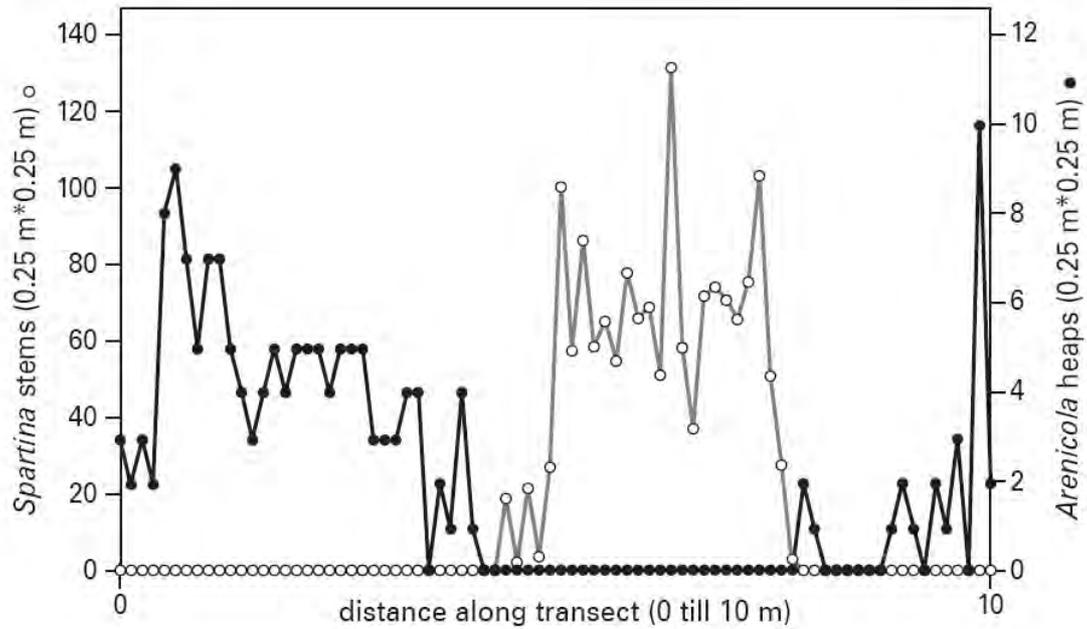
In this project, we examined this hypothesis by studying the consequences of ecosystem engineering by the common cordgrass *Spartina anglica*, on species interactions, ecosystem dynamics, and spatial structure. Our aims were twofold: first, we tried to explain the patchy distribution of *Spartina anglica* in salt-marsh pioneer zones, and to provide insight in how ecosystem engineering affects the dynamics of this zone. Second, we generalized these findings for developing a more common knowledge of implications of ecosystem engineering on species, community, ecosystem and landscape scales.

This was done through spatial characterization of salt-marsh sediment, using a combination of established (soil corer) and new ( $\gamma$ -radiation) measurement techniques ([www.medusa-online.com](http://www.medusa-online.com)). The use of natural  $\gamma$ -radiation for the spatial characterization of salt-marsh sediment was evaluated through the following questions: are there variations in  $\gamma$ -radiation at and around the salt marsh? If yes, what are these variations related to? Does the application of the method have advantages over already established methods?

## **iii. Results**

### **Ecosystem engineering in the pioneer zone**

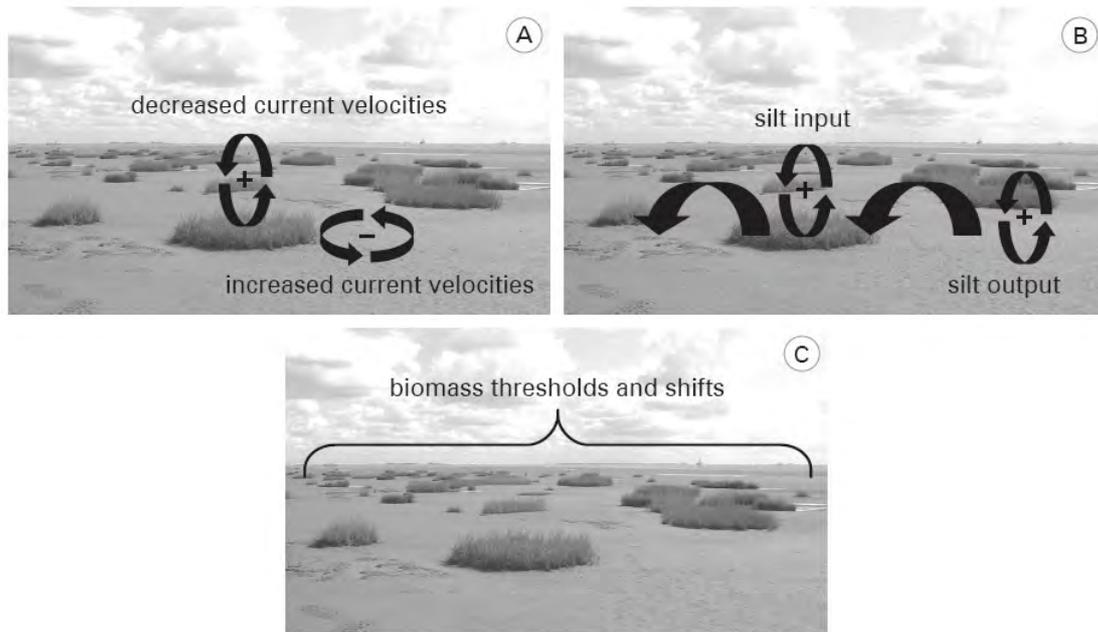
Heterogeneity in the form of strongly contrasting patches of vegetation on bare intertidal flats is considered an indicator for the presence of thresholds and alternative stable states (Fig. B-4.1a). In salt-marsh pioneer zones, ecosystem engineering by *Spartina anglica*, resulting in a positive feedback (Fig. B-4.1b), induces a threshold in vegetation response to environmental conditions. The presence of thresholds enables *Spartina* patches to persist, while existing conditions do not support the establishment of *Spartina* seedlings on bare sediment, suggesting the presence of alternative stable states.



**Fig. B-4.1:** Schematic representation of expected processes, induced by ecosystem engineering, that play a role in structuring salt-marsh pioneer zones, such as A. Decrease and increase of current velocities, B. Mutual exclusion by changing sediment properties (stabilization and destabilization), C. Biomass thresholds and shifts.

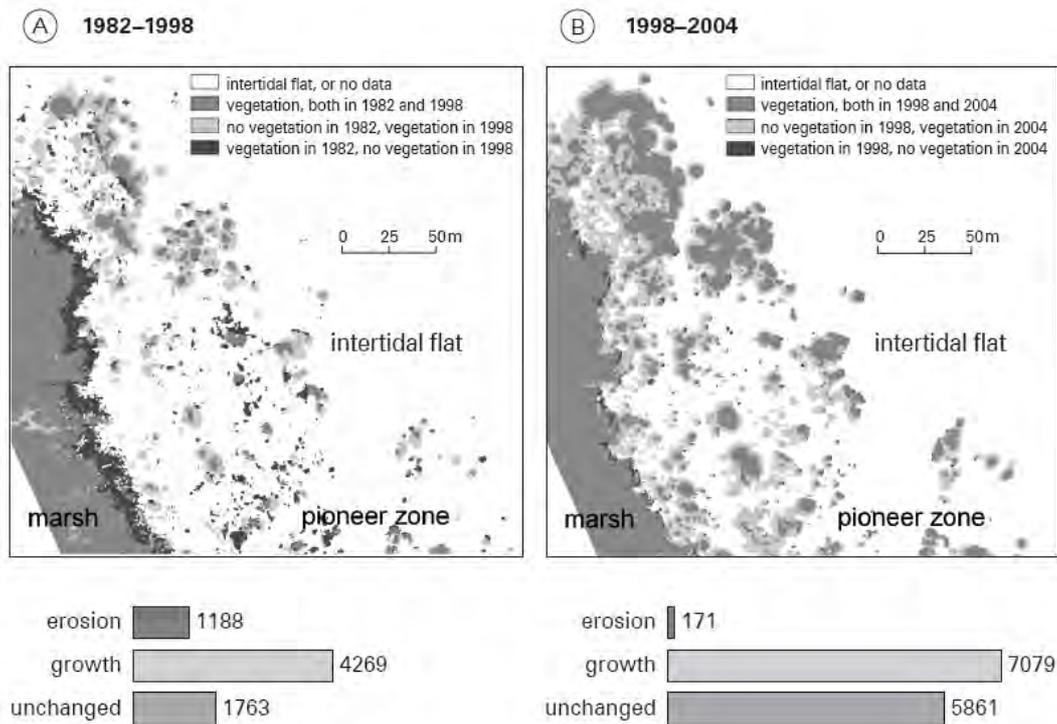
Although our experiments confirmed the presence of alternative stable states on local, within-patch scales, a study of long-term vegetation development did not support the idea of alternative stable states, as patches were found to extend and contract simultaneously on longer time scales (Fig. B-4.2).

Recruitment of *Spartina* by seedlings does not happen easily in natural systems.



**Fig. B-4.2:** Example of one transect showing *Spartina anglica* (open symbols) and *Arenicola marina* (closed symbols) distribution over an intertidal flat with salt-marsh pioneer vegetation in Krabbekreek, Oosterschelde. In general, the species did not co-occur in the same patch ( $n = 866$ ,  $P < 0.0001$ ).

Processes of recruitment were demonstrated to be very episodic, implying that in some years massive recruitment events take place, while in other years seedlings are almost absent. From the established seedlings few are able to survive. Especially in areas that are occupied by the lugworm *Arenicola marina*, seedling survival is low. From our transplanting experiments, where we transplanted different sizes of *Spartina* (seedlings, 1-2 stems and 20 stems), it became clear that in many areas with *Spartina* tussocks settlement by seedlings on bare sediment was unsuccessful. Transplanted higher biomasses of *Spartina*, small plugs of about 20 stems, almost always survived. These results underline that the presence of *Spartina* tussocks in salt-marsh pioneer zones does not indicate the potential of *Spartina* to settle by seedlings. This implies that thresholds for *Spartina* disappearance and settlement are present. In many intertidal landscapes, patches of *Spartina anglica* are found to alternate with open areas dominated by the lugworm *Arenicola marina* (Fig. B-4.3).



**Fig. B-4.3:** Growth and erosion of *Spartina* tussocks in a salt-marsh pioneer zone of Paulinapolder, Westerschelde. The picture shows vegetation that had been present between an interval (dark grey), vegetation that has developed in the period (light grey) and vegetation that had eroded in this interval (black). Figure A shows the interval from 1982 – 1998 and Figure B from 1998 – 2004. Bars and numbers underneath the panels show the exact area of vegetation ( $m^2$ ) in the pioneer zone that has been eroding or growing in both periods.

Strikingly, both species are hardly ever found together in the same patch, suggesting a negative interaction between them. Our research revealed that both species transform sediment properties in opposite ways, in the patches that they occupy: *Spartina* increases the accumulation of silt, while *Arenicola* maintains more sandy sediment by increasing silt transport out of the system. This way, both species negatively affect the persistence of the other species. These negative interactions by ecosystem engineering emerged as an important structuring mechanism explaining the patchy occurrence of these species.

Ecological theory emphasizes facilitation as an important structuring interaction in stressful environment. However, the research in this project reveals that negative interactions by ecosystem engineering can play an equally important role under stressful conditions. If ecosystem engineering effects are counteracted by an organism exhibiting an opposite feedback with environmental properties, they can possibly explain patchiness in ecosystems.

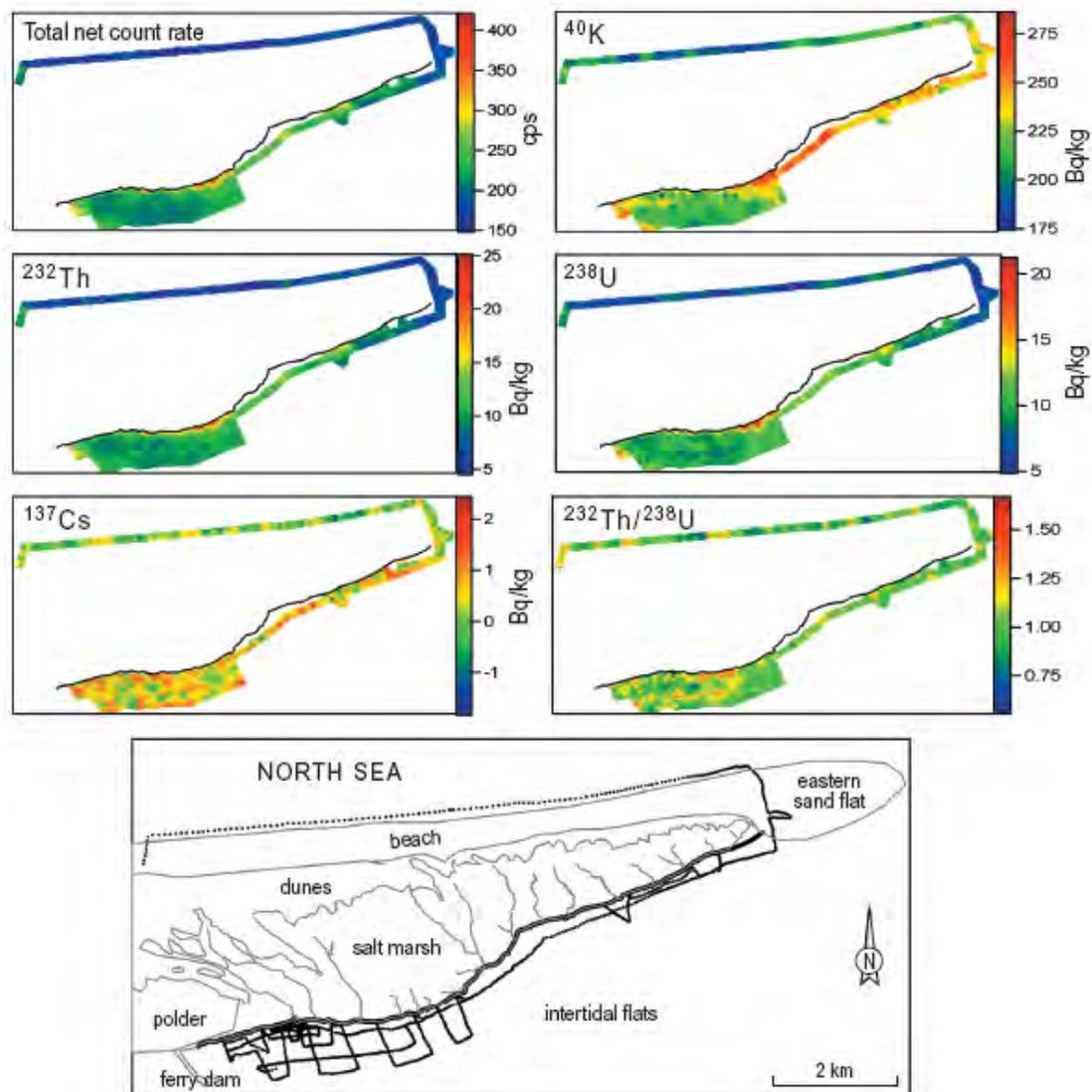
Next to problems with settlement, *Spartina* also experiences problems with expansion. Inside vegetation feedbacks were positive implying that current velocities were reduced and sedimentation increased. This resulted in a negative feedback at the borders of tussocks where increased current velocities enhanced erosion and gully formation, retarding vegetation development (Fig. B-4.1c). These gullies will form the template for future creeks in high marshes. This study demonstrates that intraspecific effects of the engineer on the environment vary with scale.

Both intraspecific and interspecific consequences of engineering are likely to depend on the environmental context as well. Flume studies showed that effects of *Spartina* on sedimentation and erosion became more pronounced with high current velocities and were almost absent with low water currents. This implicates that intraspecific engineering effects of a species on the environment subside with decreasing stress, confirming the idea that engineering is more important with high stress conditions. Interestingly, this suggests that engineering effects of a species on the environment may not exist in the absence of stress. Further, the presence of thresholds and non-linear response implies that salt marshes may still show sudden state changes, despite the absence of alternative stable states.

### **Development of the salt marsh**

Measurements of  $\gamma$ -radiation, done both in-situ and on sediment samples revealed that there are spatial variations in natural  $\gamma$ -radiation at and around the salt marsh. These variations are mainly related to the grain size of the sediment: fine-grained salt-marsh sediment (e.g., silt and clay) can be radiometrically distinguished from sand from the intertidal flats and dunes. These variations are however obscured by variations in the water content of the sediments. We developed a method to correct for this, which works well for situations that have vertically homogeneous and known water contents.

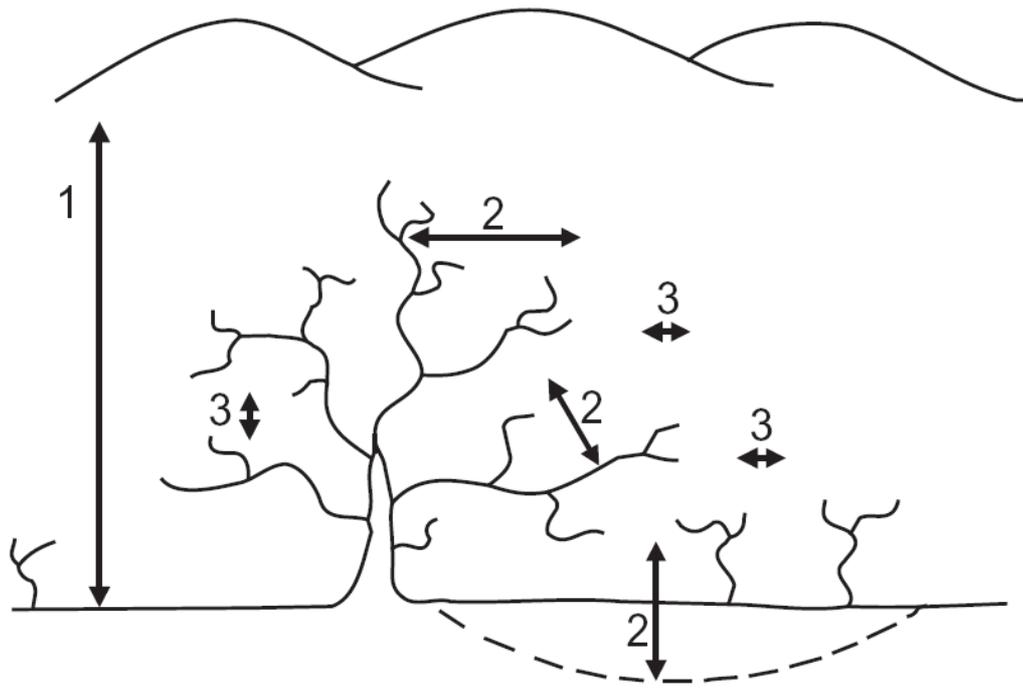
The radiometric method is in principle capable of distinguishing between the fine-grained sediment that constitutes the salt-marsh deposits and the underlying sand. On the salt marsh, it was possible to use in-situ  $\gamma$ -radiation for reproducing the general trend in top-layer thickness, as measured from soil cores, within a factor two to four. Better agreement was not possible as natural variations in water content and sediment composition affect the measured signal too strongly. Although the uncertainty in the soil-corer (manual) method turned out to be somewhat larger than expected (1–2 cm instead of 1 cm), the uncertainties in the radiometric method are still too large to compete with the traditional soil coring. Therefore, the radiometric method is not suited for measuring accretion rates on the scale of months to a few years, as required for quantifying marsh sedimentation. The method is most suited for quick-scans (e.g. from an airplane if flying low), producing qualitative maps of top-layer thickness in potentially less time than with soil cores. In contrast, the radiometric method was successful in – at least qualitatively – reproducing known patterns of grain-size distribution on the intertidal flats, with higher spatial resolution than existing maps and much less sampling effort (Fig. B-4.4).



**Fig. B-4.4:** Radionuclide activity concentrations on part of the intertidal flats and beach of Schiermonnikoog measured in situ with the PANDORA detector. Higher values indicate a larger contribution of fine-grained sediment. The thick solid line indicates the transition between intertidal flats and salt marsh at the time of measurements. Data points (dots) are given in the lower panel, together with the topography of the area.

Traditional soil cores demonstrated that the environmental conditions during salt-marsh formation vary spatially within a marsh. Part of the marsh develops under calm conditions and part under conditions rough enough for the transport of sand. The spatial distribution of the conditions is related to the slope of the underlying sand surface, in combination with the presence of dunes or artificial sand dikes that provide shelter from overwash and aeolian activity from the direction of the open sea.

As the marsh evolves, the layer of marsh deposits increases in thickness and forms spatial patterns that change in size and structure through time. There are at least three hierarchical levels in these spatial patterns, indicating that controls on sedimentation act on all spatial scales (Fig. B-4.5).

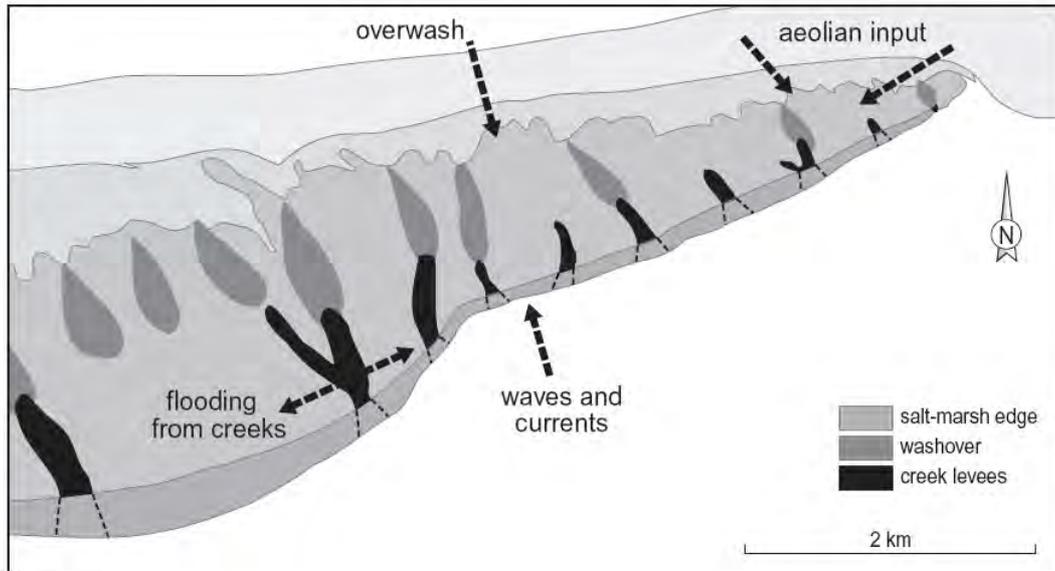


**Fig. B-4.5:** Schematic overview of the hierarchical spatial scales in salt-marsh accretion and their forcings. Number 1 represents the gradient in base elevation from the dunes to the intertidal flats; numbers 2 represent the distance to the nearest sediment source, influenced by creek development and lateral marsh growth; numbers 3 give the local influence of e.g. the vegetation.

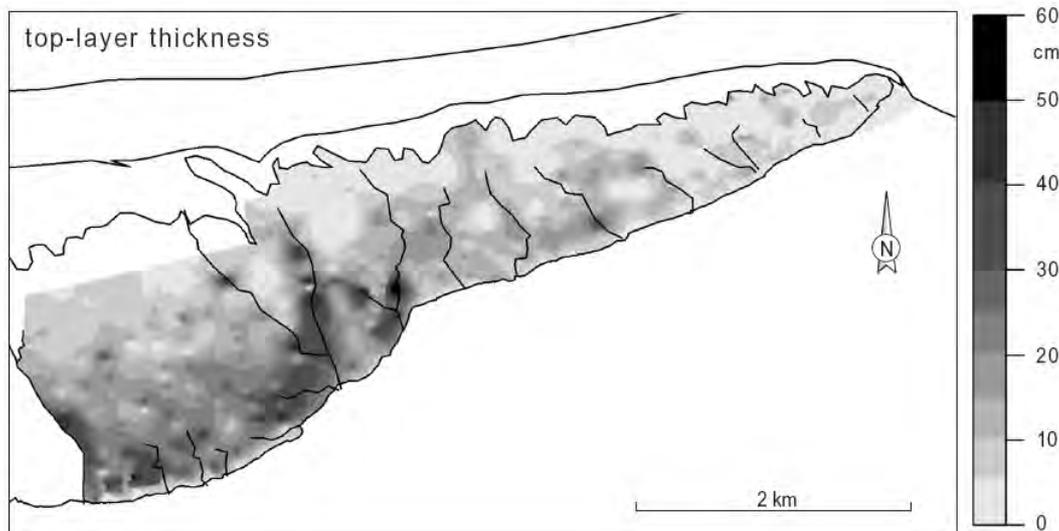
On the largest scale (number 1 in Fig. B-4.5), the elevation of the underlying sand surface is the initial control on inundation frequency and duration, setting the potential for future sedimentation. Its influence decreases during marsh development, when independent accretion patterns develop. The independent patterns are most probably created by the ongoing creek development, including levee development, and lateral marsh growth, (numbers 2 in Fig. B-4.5).

Both processes affect the distance of a certain location on the marsh to the nearest sediment source, which is the second important control on marsh accretion. Finally, on the local scale (number 3 in Fig. B-4.5), vegetation may create irregularities on the marsh surface and lead to variations in current velocity.

Spatial patterning is observed, too, in sand layers that occur within the salt-marsh deposits. They are the result of severe storms, during which waves and currents may take up sand from the intertidal flats and creek bed and deposit it on the marsh surface, within a limited distance from the salt-marsh edge and creeks. Additionally, water from the open sea may breach through the dunes and deposit sand eroded from the beach and dunes. Sand from dunes or areas left bare by overwash may subsequently be taken up by the wind and deposited on the marsh. The sand layers were dated using the known ages of the salt marsh. The occurrence of sand-depositing storms on Schiermonnikoog has been approximately decadal, although an increase in sand deposition and extreme tide levels were observed in the past few decades. This may be related to the overall increase in high-tide levels in the Dutch Wadden Sea.



**Fig. B-4.6:** Schematically representation of dominant sand deposits on the salt marsh of Schiermonnikoog, based on measurement results.



**Fig. B-4.7:** Upper panel: map of top-layer thickness on the salt marsh on Schiermonnikoog, interpolated using kriging. Lower panel: standard deviations of the interpolated values. Dots represent measurement locations.

The locations with most sand layers (Fig. B-4.6) resemble those where top-layer thickness is generally largest (Fig. B-4.7): along the salt-marsh edge and creek levees. The patterns for both types of sediment reflect the proximity to the sources of sand, wind and water. The sand layers were mostly deposited at the time a certain marsh area was relatively young. This indicates that, again in analogy with the fine-grained sediment, ongoing creek development, lateral marsh growth and further dune building affect the accessibility of the marsh to sand, wind and water, and thus affect the depositional patterns.

#### **iv. Conclusions**

##### **Pioneer zone**

In many cases the positive feedback between *Spartina* and sedimentation forms the basis for salt-marsh formation. Under ideal conditions, *Spartina* can rapidly invade a bare intertidal flat and form a homogeneous vegetation cover. Capturing of fine-grained sediment by *Spartina* stands, raises soil elevation and makes the habitat suitable for invasion of other salt-marsh plants. However, many salt marshes in the Netherlands are eroding and *Spartina*, if present at all, is found in scattered patches on the intertidal flat. Several processes that are spin-offs of ecosystem engineering on local scales, can limit expansion of present *Spartina* tussocks and prevent recruitment of new seedlings.

First, ecosystem engineering can induce positive feedbacks on local, within-patch scales, with resultant negative feedbacks on larger, between-patch scales. These feedbacks can limit tussock expansion and, consequently, give rise to more complex structures on ecosystem or landscape scales. Furthermore, ecosystem engineering can be a mechanism for negative species interactions, resulting in exclusion and patchy species distributions in ecosystems. Further, habitat modification is found to give rise to thresholds in ecosystems, resulting in unpredictable and irreversible ecosystem changes in response to environmental change. Finally, ecosystem engineering can generate the development of strong contrasting habitats along gradients of stress. For all these effects it should be kept in mind though that they vary considerably depending on environmental background conditions and spatial scale.

##### **Salt marsh**

Most of the findings were based on measurements from Schiermonnikoog, which is a long-term study site for salt-marsh ecology and was therefore the first choice for conducting field research. The surveys involving soil cores on Terschelling and Skallingen show that, on the investigated high and middle marsh (sub-catchment scale), the general pattern is comparable. There are only small differences between the islands in past environmental conditions as identified from the sediment record and spatial patterns in accretion. The relation between top-layer thickness and in-situ  $\gamma$ -radiation was also comparable between the investigated marshes. It is therefore expected that the findings on marsh development are generally applicable.

One of the initial questions was to identify sources and sinks of sediment in relation to salt-marsh rejuvenation. Unfortunately, with both the radiometric and corer methods, it was not possible to recognize sources and sinks of the fine-grained sediment within the marsh of Schiermonnikoog. The radiometric fingerprint of the fine-grained sediment seems to be homogeneous within the Dutch Wadden Sea. The most probable explanation for the small-scale variations in radionuclide concentrations of the sediments at and around the salt marsh are thus variations in the hydrodynamic conditions under which the sediment was deposited.

#### **v. Recommendations**

For successful restoration and conservation of salt-marsh systems it should be kept in mind that vegetation development often is a slow process. It might be a profitable strategy to create benign physical conditions for vegetation settlement and growth, on a temporary basis, for example by

using brushwood groynes. Once vegetation is actually present with high biomass it is expected to be rather resilient to changes. Still, our results suggest that salt-marsh pioneer zones have the capacity to suddenly shift from a vegetated to an unvegetated state in response to environmental changes.

Future research should extend on the conceptual framework that we developed for negative species interactions via the environment, including both empirical and modeling studies. Furthermore, it will be interesting to examine whether engineering effects of a species on the environment, can only be detected under high stress conditions and are absent when conditions are benign. Another line of research that is worth pursuing is investigating the implications of patchiness in ecosystems and, specifically, in transition zones between different systems. Possibly effects on transition zones can cascade through a system and affect both ecosystems that border the transition zone. A more thorough understanding of dynamics in transition zones could benefit successful management and conservation of complete ecosystems. Hypotheses should aim to examine if patchiness is a characteristic of transition zones and whether these zones are in general maintained by positive feedbacks. This will give insight into the vulnerability of transition zones to changes and help to estimate response of transition zones to climate change. This line of research will also allow us to predict response of salt marshes, and specifically salt-marsh pioneer zones, to future sea-level rise.

In the Dutch Wadden Sea, there is concern about the change in ecosystem functioning related to e.g. shellfisheries and the disappearance of mussel beds and seagrass beds. These changes may be reflected in sediment composition. A method that can quickly map the intertidal flats on sand and mud may therefore benefit the ongoing research on these subjects, and the radiometric method has good potential. It works best if the only differences in radiometric fingerprints are between the fine-grained sediment and sand. Therefore, a pilot experiment in which the fingerprints are established should always be done before applying the method to a new area.

The presence of multiple levels of spatial patterns in salt-marsh accretion has implications for measuring salt-marsh accretion. To obtain reliable values for accretion, measurements should sufficiently sample the extent of the patterns. As the size of these patterns is difficult to predict beforehand, it is wisest to spread measurements as much as possible over the entire area of interest. Predictions of salt-marsh resilience to sea-level rise that are based on only a few measurements, spatially clustered measurements, or data from only one marsh zone should therefore be treated with caution.

Currently, there is much interest in the importance of overwash deposits for the functioning of salt marshes on barrier islands, related to the presence of artificial sand dikes on the Dutch Frisian islands. The exploratory study in this project indicates that the total contribution of sand from washover deposits to the salt marsh on Schiermonnikoog is in the order of one or two percent. Under the current conditions, the active marsh does thus not rely on washover sediment for keeping pace with sea-level rise. For the development of the distal end of the island as a whole, however, the contribution of washover deposits may be much more important for instance by creating accommodation space for marsh growth and introducing landscape variety.

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