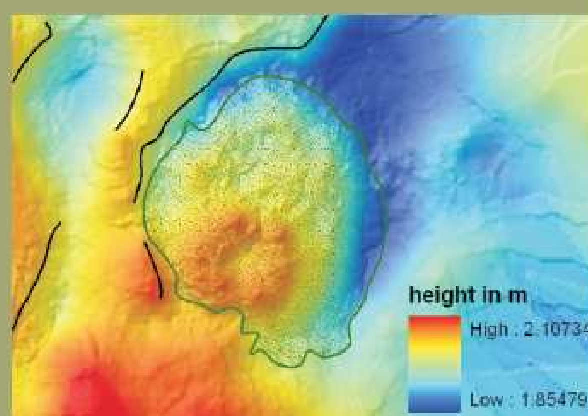
Biogeomorphology of *Spartina anglica* tussocks

GIS based comparison of contrasting sites at the Westerschelde and Blackwater estuary



Thorsten Balke

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GIS based comparison of contrasting sites at the Westerschelde and Blackwater estuary

Freie wissenschaftliche Arbeit zur Erlangung des Grades eines Diplom-Geographen am Institut für Physische Geographie und Landschaftsökologie der Leibniz Universität Hannover

vorgelegt von: Thorsten Balke
Erstprüfer: Prof. Dr. G. Kuhnt
Zweitprüfer: Prof. Dr. P. M. J. Herman

Hannover und Yerseke, im April 2009

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1 Abstract

English:

Spartina anglica is a dominant species in the pioneer zone of European salt marshes and has been widely planted in the first half of the 20th century for coastal protection and land reclamation. The effect of this invasive species is still poorly understood, positive and negative effects on sedimentation or habitat alternation have been described. The seaward edge of a Spartina anglica salt marsh consists of tussocks with mainly clonal expansion. Because Spartina anglica is an autogenic ecosystem engineer, understanding the expansion and dieback processes of these tussocks is important for coastal protection and nature conservation issues. With extensive fieldwork at contrasting sites in the Netherlands and England as well as a visit to the German Wadden Sea the biogeomorphology of 83 single tussocks were analysed with GIS.

This thesis shows that tussock topography is different between sites and is mainly depending on the overall sedimentation- erosion processes and hydrodynamics of the tidal environment. Tussocks can be elevated or sunk-in whereas Spartina anglica is reaching its limits of ecosystem engineering in some cases. The height differences have an effect on lateral expansion and erosion rates of the tussocks whereas growth rates show a dominating size dependency.

Deutsch:

Seit der extensiven Anpflanzung für den Küstenschutz und zur Landgewinnung in der ersten Hälfte des 20. Jh., dominiert Spartina anglica die Pionierzone der europäischen Salzwiesen. Die Auswirkungen dieser invasiven Art sind noch immer nicht eindeutig geklärt. Beobachtet wurden postive als auch negative Effekte auf Sedimentation sowie Habitatveränderungen. Die äußersten Bereiche der Spartina Salzmarschen bestehen aus Horsten (Bulten) mit hauptsächlich vegetativem Wachstum. Da Spartina anglica seine abiotische Umgebung maßgeblich beeinflusst, ist das Verständnis des Wachstums und Rückganges dieser Horste bedeutend für den Küsten- und Naturschutz. Extensive Feldarbeit in den Niederlanden und in England sowie ein Besuch des Deutschen Wattenmeeres haben die Analyse der Biogeomorphologie von 83 einzelnen Horsten im GIS ermöglicht. Diese Arbeit zeigt, dass die Form der Horste stark variiert und von den allgemeinen Sedimentations- und Erosionsprozessen sowie Strömungen im Gezeitenbereich abhängt. Es können erhöhte oder versenkte Horste entstehen, wobei dies Einfluss auf die Entwicklung der Horste nimmt. Die Wachstumsraten sind im Allgemeinen von der Größe der Horste abhängig.

2 Introduction and motivation

The border between land and sea is an extreme habitat where only halophytes can survive. But salinity is not the only stress factor, hydrodynamics and sediment dynamics can also change survival chances in intertidal environments.

At parts of the Westerschelde salt marshes form the coastline in front of the dykes, they provide ecosystem, economic and cultural values like important fish and bird habitat, sea defence, water quality improvement, recreation and landscape structure, “which begin to take shape as soon as the first plants take root in the tidal mudflats” (DOODY 2008).

The pioneer zone of the salt marsh, which can extend down to mid-tide level, is dominated by the patchy vegetation of the Common Cordgrass (Spartina anglica). Spartina anglica is a hybrid of Spartina maritima and Spartina alterniflora, first identified in Britain at the beginning of the 19th century and then exported into the world for coastal defence because of its ability to enhance sedimentation. It is occupying a niche where only the rather scarce vegetation of Salicornia spp. is also able to live and can therefore enhance the sediment accretion of salt marshes. Although it was exported and established throughout the world a long time ago the ability to enhance sedimentation and its value for coastal defence is still discussed. Moreover the influence of an invasive species like Spartina anglica on a salt marsh ecosystem can be harmful (DOODY 2008).

The interaction between plant growth and sedimentation gained a lot of interest in the Westerschelde because of the high values of its salt marshes. This thesis is incorporated in a STW (technology foundation) funded project which aims to describe the potential coastal defense by management of coastal ecosystems.

Several studies about salt marsh cycles, sedimentation patterns, cliff erosion, and seedling survival in salt marshes along the Westerschelde have already been carried out at the Netherlands Institute of Ecology (BOUMA et al. 2007, BOUMA et al. 2009, VAN DE KOPPEL et al. 2005, VAN DER WAL et al. 2007, VAN HULZEN 2007, VAN WESENBEECK et al. 2008).

This study is focusing on the pioneer zone of salt marshes where patchy Spartina anglica vegetation is dominant, especially the way in which vegetation patches erode or expand and how they influence their environment is adressed to gain knowledge in salt marsh dynamcis.
Three main hypotheses will be covered within this thesis:

(1) Tussocks have different shapes i.e. topography which depend on their environment.
(2) Tussock development (expansion, erosion) is different between different shapes.
(3) Spartina reaches its limits of ecosystem engineering under extreme conditions.

Patchy vegetation in form of clonal tussocks or shrubs often exists in extreme environments with harsh conditions where they interact with the abiotic environment. Nebkhas (vegetated dunes) in deserts (WANG et al. 2008) or reed patches in semi-arid rivers (KOTSCHY and ROGERS 2008) are examples in a contrasting ecosystem but with similar processes as Spartina patches in tidal environments. To understand the dynamics of patchy clonal vegetation is important to understand the development of extreme habitats which are sensitive to changes.

3 Biogeomorphology

Biogeomorphology is describing the link between ecology and geomorphology, it is interdisciplinary and hard to define. Whereas Darwin was already working on the biogeomorphology of earthworms a lot of research has been done on this topic with different names e.g. geoecology, zoogeomorphology, phytogeomorphology or deondrogeomorphology and so on in the 20th century. Biogeomorphology is used as an umbrella term for all topics of this field. Today there are three recent topics within biogeomorphology which differ in time scales and spatial scales:

- effects of organisms on geomorphic processes
- contribution made by organic processes to the development of landforms
- impact of geomorphological processes on ecological community development

Whereas bioturbation of moles or gophers are an example for active biogeomorphology the sedimentation within mangroves or salt marshes is a passive biogeomorphological process. This topic has a wide application and can be of practical use because organisms often have a protective role as they delay geomorphic processes e.g. in coastal environments or on agricultural land (GOUDIE 2004).

There is a recent trend in interdisciplinary work of addressing combined organic and inorganic processes.

The term of ecosystem engineering is a young concept which was first introduced about 10 years ago and develops the idea of biogeomorphology a bit further. It focuses on "how organisms physically change the abiotic environment and how this feeds back to the biota" (HASTINGS et al. 2007). Sphagnum spp. for example causes major changes in the hydrology, topography and pH of a bog due to water logging. It modifies the abiotic conditions and even creates a new habitat (JONES et al. 1994).

Organisms can cause positive or negative feedbacks on the habitat which can even outlive the ecosystem engineer.

As in biogeomorphology passive and active processes are distinguished.

Autogenic ecosystem engineers change their physical environment only due to their physical structure i.e. with their presence and allogenic ecosystem engineers change their environment via an activity (JONES et al. 1997).

Spartina anglica is considered to enhance sedimentation due to its presence which has an effect on soil properties and therefore on the habitat, hence Spartina anglica is an autogenic ecosystem engineer (VAN HULZEN et al. 2007, BOUMA et al. 2009).

4 *Spartina anglica*, an invasive species

4.1 The history of Spartina anglica in Europe

Spartina anglica (see Fig. 4.1) is a species with a short but eventful history beginning in England.

The indigenous Spartina maritima and Spartina alterniflora (brought to the UK in 1816 from the USA) produced a sterile hybrid, Spartina x townsendii.

After doubling of its chromosomes a new and fertile Spartina species, described as Spartina anglica, appeared in England 1892 (DOODY 2008).

Only 32 years later, between 1924 and 1936, 175000 rhizomes were exported to 130 places all over the world because Spartina anglica was considered to be beneficial for coastal protection and of great use for land reclamation.

The Netherlands were the first to receive Spartina anglica fragments from Poole Harbour in England and planted them in the Zuid Sloe area which is a part of the Westerschelde.

The first establishment of Spartina anglica in the German Wadden Sea took place in 1927. Today, 75 years after the first planting, it is still doubtful if Spartina anglica had a positive impact on coastal protection (NEHRING and HESSE 2008).

Spartina anglica C.E. HUBBARD

English: *Common cord grass*
Dutch: *Engels slijkgras*
German: *Englisches Schlickgras*

Identification:
Stout rhizomatous salt marsh grass with round hollow stems five mm or more in diameter. Ligules (a) consist of fringe of hairs: 2-3mm S. anglica, 0.3-2mm S. x townsendii. Leaves are 36 to 46cm in length and 5 to 13mm broad, rough and green-gray. Colourless flowers in erect contracted panicles with closely overlapping spikelets in two rows.

Habitat:
Salt marshes and tidal flats throughout the world between MHWN and MHWS prefering muddy and sheltered sites.

(CONERT 2000; NEHRING and ADSERSEN 2006; SCHMEIL and FITSCHEN 2006)

Fig. 4.1 Spartina anglica (CONERT 2000)

4.2 Coastal protection or destruction of habitats?

Because Spartina anglica can tolerate inundation periods of up to 9 hours it occupies the lower elevations of the salt marsh and can grow between MHWN and MHWS.

Therefore it mainly replaces Salicornia spp. vegetation in the pioneerzone or colonises the bare mudflat which causes a drastic change in vegetation cover. Where continuous Spartina anglica swards replace bare mudflats, sedimentation rates are significant higher and the sediment gets stabilised (NEHRING and HESSE 2008).

In general sedimentation rates within a S. anglica salt marsh are considered to be 10 times higher than a natural non Spartina salt marsh (Doody 2008).

A study on Spartina alterniflora on cobble beaches in New England discovered flow reduction of mean flow behind S. alterniflora of app. 40%, moreover the bed was found to be more stable behind than between patches. Removal of the vegetation showed an 85% increase in substrate instability (BRUNO and KENNEDY 1999).

To which extend patchy vegetated areas enhance sedimentation and stabilisation is not yet clear but VAN HULZEN et al. 2007 found finer grain sizes of sediment within S. anglica patches than next to it, which has been described as an indicator for enhanced sedimentation, but also the existence of scouring holes around the tussocks have been found which prove erosive processes due to vegetation presence.

One reason that Spartina anglica's coastal protection properties are doubted is that it favours sheltered sites: "the common cordgrass can not protect any coast, it grows well only there where it is protected itself by the coast" (KOENIG 1948 in NEHRING and HESSE 2008). Also in recent publications WIDDOWS et al. 2008 state that "the Spartina anglica salt marsh should not be considered a 'bio-stabiliser' of fine muddy sediment" and that the presence of the stems even enhances turbulence and therefore erosion.

Besides the discussion about coastal protection it is no longer doubted that the rapid expansion mainly of Spartina anglica and alterniflora is a thread for wildlife and natural salt marsh succession (Doody 2008, NEHRING and HESSE 2008).

The invasion of S. anglica has four main impacts on the salt marsh ecosystem: (1) competition, (2) habitat alteration, (3) genetic impact and (4) disease impact.

(1) S. anglica outcompetes natural salt marsh vegetation especially in the pioneerzone with building mono structured swards. (2) There is evidence, that macrobenthos and microbenthos is absent in S. anglica vegetation as it spreads into the mudflat.

Also the change in sediment composition, oxygenation and the higher sedimentation cause long lasting changes of the habitat. (3) As the genetic alteration of Spartina x townsendii to S. anglica was rapid, it is likely that new variations could arise. (4) The infection of complete Spartina anglica swards by the Spartina mottle virus and the fungus Claviceps purpurea were reported.

However all these impacts are known, detailed quantifications of threats and benefits on conservation and coastal protection issues are still missing (NEHRING and HESSE 2008).

Despite the lack of research, several biological and chemical control measures have already been tried to eradicate invasive Spartina spp. and especially in the US hundreds of volunteers gather to manually remove Spartina alterniflora rhizomes which seems to be the only promising method.

Due to its growth from rhizomes treatments like trampling, crushing, burning and digging are not effective, rotovation is even counterproductive because the rhizomes get distributed and can propagate. The only method next to the work intensive manual removing is treatment with herbicides like Dalapon and Glyphosate (DOODY 2008).

Because S. anglica has shown a natural die back after establishment in some places (see following chapter) DOODY 2008 suggests that leaving things alone could be the only thing that is needed to control Spartina anglica.

4.3 Expansion and die back cycles

S. anglica sprouts in spring and produces wintering buds in November, rhizome development takes place in autumn and early winter whereas the flowering culms of the previous season usually die during winter.

The production of seeds is variable and not predictable, it is suggested that in the early stages seed production is low and it is increasing with marsh development. Moreover warm temperatures in late summer seem to increase seed production.

The seeds S. anglica produces do not form a persistent seed bank, field observations from England show that they are only viable for one season (NEHRING and ADSERSEN 2006).

Besides seedling distribution S. anglica can also spread through broken fragments dispersed by water flow or anthropogenic influence. CHATER and JONES 1957 described for example an increased spread of Spartina townsendii after World War II in the Dovey estuary due to the use of military vehicles in that area.

The theoretical process how S. anglica colonises the mudflat starts with initial spread of seedlings. After successful establishment Spartina can form circular tussocks with mainly clonal growth until they form a continous sward, the lateral expansion rates of a tussock can be up to 30-50 cm/year (NEHRING and ADSERSEN 2006).

However this process can stop at some point and tussocks remain stable for several years.

It is also possible that under favourable conditions no tussocks get formed and S. anglica just spreads via seedling establishment until it is dense enough to be called a meadow or sward.

The story gets even more complicated if we look at die back processes which have been reported for S. anglica and S. alterniflora.

This can happen in two ways, either in a lateral die back due to wave impact or in large areas within continous swards. This process could be due to “water logging and sooft-rooting of the apex of the rizome” (GOODMAN 1960 in DOODY 2008).
Also ice drifting in extreme winters seems to harm S. anglica extensively (VINTHER et al. 2001) but in most cases S. anglica recovers from its losses.
In case of a single tussock it is likely that a small change in environmental conditions, e.g. inundation period, could kill the whole tussock at once because it is only one individual (VINTHER et al. 2001).

4.4 What is known about Spartina spp. tussocks?

4.4.1 Research on Spartina salt marshes

The colonisation of Spartina spp. on a bare mudflat always interested scientists around the world. Research on Spartina has been done in different ways in the USA in Europe and in China.
Most researchers where interested in Biomass production and spread of Spartina anglica or Spartina densiflora and its possibilities to control this invasive species in general (CALLAWAY and JOSSELYN 1992; HAMMOND 2001; NEHRING and HESSE 2008; VINTHER et al 2001; MATEOS-NARANJO et al. 2008).
Also some hydrodynamic and geomorphological studies were done to compare Spartina dominated salt marshes to “natural” salt marshes (WIDDOWS et al. 2008; LEONARD et al. 2002, SHEN et al. 2008).
Because Spartina often colonises by clonal growth in form of circular vegetation patches, some researchers focused on Spartina tussocks with different interests from a landscape scale to nutrient concentrations within tussocks.

4.4.2 Domes and gullies

Many authors propose that the typical topography of a tussock is dome shaped or hummock like due to enhanced sedimentation in the vegetation (CASTELLANOS et al.1994, VAN HULZEN et al. 2007, SANCHEZ et al. 2001, VAN WESENBEECK et al. 2008). CASTELLANOS et al. 1994 describes dome shaped Spartina maritima tussocks in an estuarine complex in SW Spain. He shows that tussock size is positively correlated to the elevation of the tussock to hydrographic zero, suggesting that larger tussocks at higher elevations represent earlier establishment and faster growth (Fig. 4.2). But by taking the highest point of the tussock as the height he makes the relationship less believable because tussock dome height increases with tussock size. SANCHEZ et al. published further analysis of dome shaped S. maritima tussocks in north-west Spain in 2001. With simply measuring the height difference between tussock and surrounding mudflat he finds a description for accretion of each tussock. His data analysis shows that tussock diameter is the main factor which determines the dome height and hence the accretion within a tussock. Furthermore he states that this relationship is non-linear because it reaches a limit with a certain size of the tussock (Fig. 4.3).

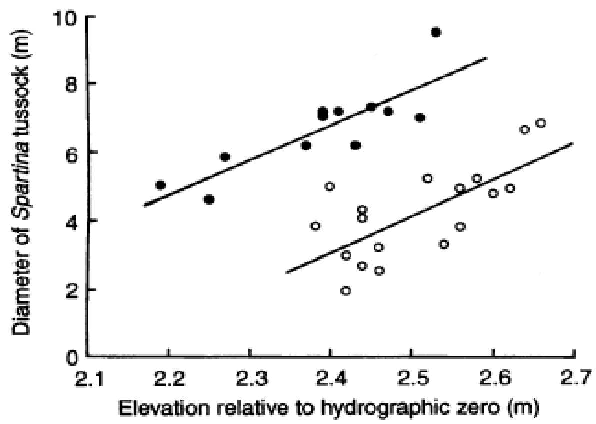


Fig. 4.2 Diameter and elevation of upper surface of S. maritima tussocks at two sites at Odiel marshes, SW Spain (CASTELLANOS 1994)

Population A is situated closer to open sea which goes along with higher sedimentation rates. No relations between shoot characteristics and accretion are found (SANCHEZ et al. 2001).

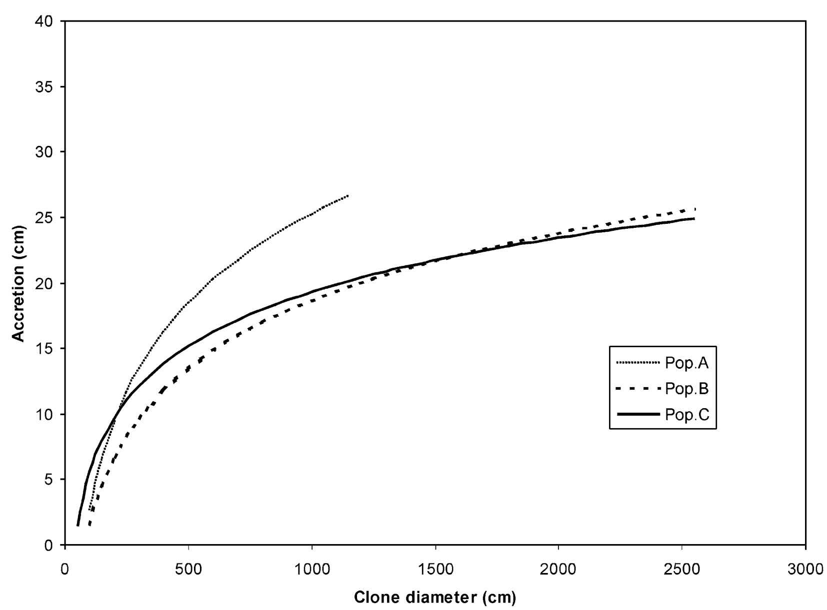


Fig. 4.3 Tussock diameter and dome height as a proxy for accretion of 3 sites in NW Spain (SANCHEZ et al. 2001)

The same evidence for sediment trapping is documented for Spartina foliosa patches at the Tijuana estuary. Tussocks with a dome height between 6 and 18cm were observed. The result that the elevation range within tussocks is not related to clone diameter does not fit with the observations of SANCHEZ et al. 2001. The bulk density is greater on the mudflat than in the tussocks and lateral expansion rates of up to 130cm/year are found to be very variable in time but slightly increasing with elevation.

Sedimentation is generally higher within the vegetation but under ENSO *(*El Niño-Southern Oscillation*)* conditions, where sedimentation rates of 10cm/ year occurred, sedimentation is the same within and next to the tussocks (WARD et al. 2003).

Focusing on habitat modification of Spartina anglica, VAN HULZEN et al. 2007 describes for the Westerschelde that the sediment accretion and hence the dome shape of tussocks has a positive effect on plant growth by e.g. reducing inundation stress and enhancing drainage.

He suggestes that the dome shape of the tussock also causes gully erosion due to enhanced current velocities around the mounds (VAN HULZEN et al. 2007).

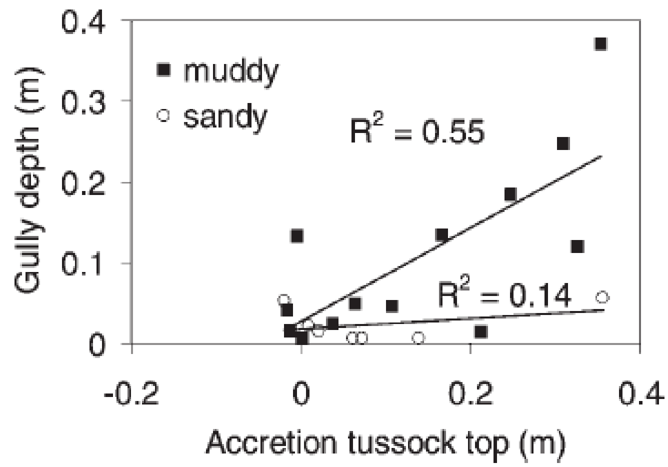


Fig. 4.4 Dome height and gully depth of S. anglica tussocks at muddy and sandy sites (VAN HULZEN et al. 2007)

Figure 4.4 shows the relation between height of dome and depth of gully, the graph does not include the size of the tussock which is an important factor.

He further hypothesizes that there is a trade-off between shoot density and lateral expansion, because higher shoot density is likely to cause gully erosion around tussocks, which can hinder lateral growth, whereas higher shoot density leads to more sedimentation and hence better growth.

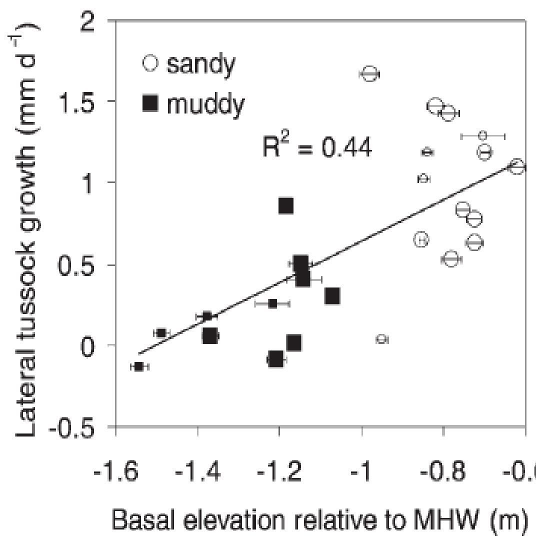


Fig. 4.5 Lateral growth (1997-1999) and elevation of tussock to hydrographic zero at sandy and muddy sites (VAN HULZEN et al. 2007)

This is explained with the finding that tussocks with higher shoot density are situated at lower elevations at the mudflat, and those are the same that also showed gully formation (VAN HULZEN et al. 2007). His second hypothesis is another trade-off between "capacity of maximal clonal expansion by spreading shoots widely versus the risk of tussock mortality due to insufficient modification of the habitat, which makes the tussock vulnerable for erosion" (VAN HULZEN et al. 2007). He estimates the lateral growth between 1-60cm/year whereas he finds a difference between elevations of the tussocks. But if you look at the relation at the muddy and at the sandy site separately (Fig. 4.5) this correlation becomes less significant.

Also VAN WESENBEECK et al. 2008 showed that tussock size and dome height are positively correlated, as well as gully depth and height multiplied by size of tussock.

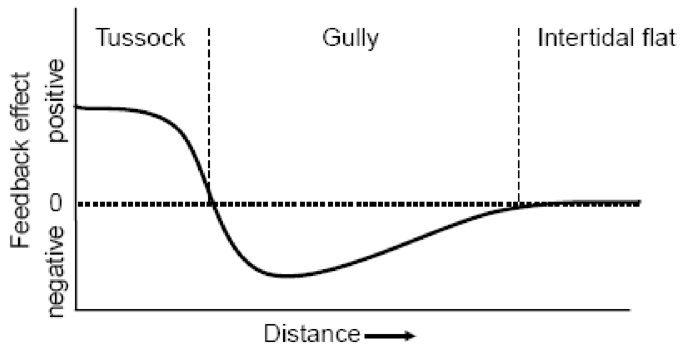


Fig. 4.6 Schematic representation of feedback effect of tussocks (Van Wesenbeeck et al. 2008)

Her work at the Westerschelde focuses on scale dependent feedbacks (Fig. 4.6) and includes flume experiments to examine gully erosion which was observed in the field. Half of the flume width (60cm) was filled with S. anglica (1m long) and flooded at different water heights. The developing gully in the other half of the flume width showes positive correlation with velocity and negative correlation with water depth (Fig. 4.7). This gully erosion is a causing negative feedback next to the tussock, which has been proven by transplanting Spartina seedlings at different distances from the tussock centre in the field. Growth is higher in the tussock vegetation and lower within the gully compared to transplants on the bare flat. Moreover the dimensions of the gullies have a significant positive correlation with dome volume (VAN WESENBEECK et al. 2008).

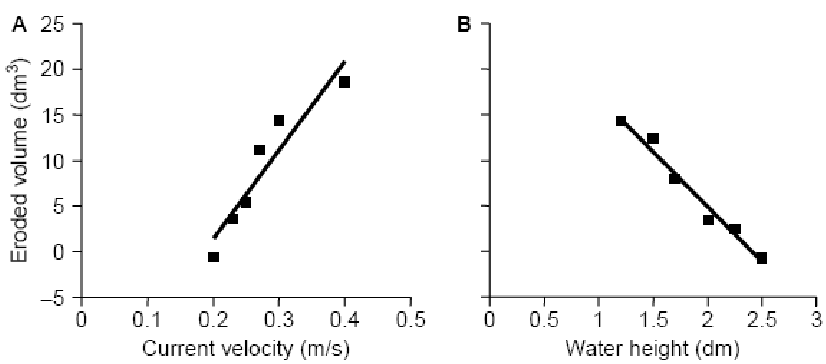


Fig. 4.7 Gully erosion measurements in a flume experiment related to water height and current velocity. Shallow water causes more erosion. (Van Wesenbeeck et al. 2008)

4.4.3 Hydrodynamics and patchy Spartina vegetation

Field measurements, flume experiments and 3D modelling have been done on Spartina patches. Most of the studies yield to explain the facilitation or ecosystem engineering properties of this species. BRUNO and KENNEDY 1999 show with ADV (Acoustic Doppler Velocimeter) field measuerements that Spartina alterniflora patches reduce flow velocities about 40-60% (measured behind the patch) which lead to an increase in substrate stability. Especially the stabilisation of the substrate leads to a facilitation of other species, the extent of this habitat modification by Spartina alterniflora patches is size dependent, smaller patches are not able to reduce the flow as much as bigger patches (BRUNO and KENNEDY 1999).

A more multidisciplinary and experimental study is done by BOUMA et al. 2007.

Artificial patches made of several bamboo sticks pushed into the sediment (Fig. 4.8) simulating epibenthic vegetation structes like Spartina were installed at tidal flats and salt marshes of the Westerschelde. Within a time span of 2 years the changes of the sediment surface within and around the patches were measured to estimate sedimentation and erosion due to the presence of the patch.

The hydrodynamics within these structures have also been measured in a flume and were modelled with a 3D hydrodynamic model.

Fig. 4.8 Bamboo patch at Valkenisseplaat, high density (BOUMA et al. 2007)

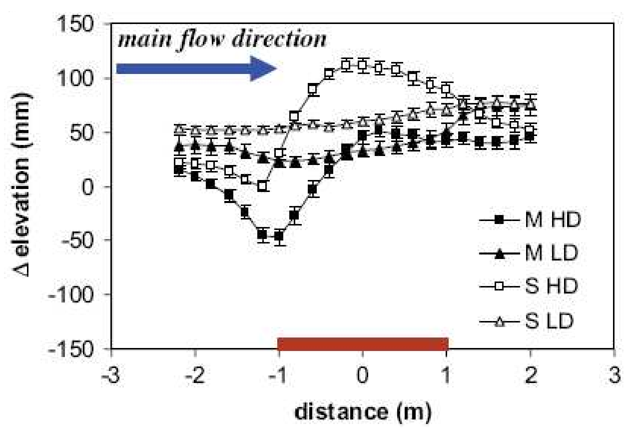


Fig. 4.9 Sedimentation and erosion next to and within tussocks (red bar) at Molenplaat. HD: high density, LD: low density, S: sandy, M: muddy. (BOUMA et al. 2007)

The flume and model results explain the sedimentation and erosion patterns observed at the bamboo patches in the field (BOUMA et al. 2007).

The patches in the field (2.2m diameter) show a different topography depending on the density of bamboo sticks. The patches with a high density (400 sticks per m²) show erosion from 1m in front of the patch to 1m into the patch (Fig. 4.9) and sedimentation in the wake zone, whereas the low density patches (25 sticks per m²) only show erosion directly around each bamboo stick, with no relevant effect on average elevation change.

Moreover the high density patches show erosion on the sides of the patch parallel to the main flow direction.

Next to the differences between densities, the sediment composition seems to have no effect on the topography but sediment within the patch has a tendency to bigger grain sizes. Also differences between different sites where observed, where some tussocks caused net erosion and some net sedimentation.

Especially the tussocks at Valkenisseplaat caused strong erosion while adjacent natural Spartina tussocks had a clear dome shape.

The flume experiments reveales the process causing the erosion at the leading edge of the bamboo stick patch.

Especially at the high density patch higher levels of Reynold stress and higher levels of TKE (Turbulent Kinetic Energy) are found at the front of the bamboo field. Because the water level is higher then the bamboo sticks, the skimming flow at high density patches causes an overall deceleration of flow within the whole structure which is close to zero at the end of the patch. The whole profile of the flume is filled with the bamboo sticks, therefore the conclusions can be only made about continuous structures without possibilities of water to flow around it (BOUMA et al. 2007).

This is modelled with a 3D hydrodynamic model (Delft-3D) which is showing the bottom shear stress. Fig. 4.10 shows high values for the sides of the patch and still relatively high values for the first cm from the leading edge which is also observed in the field as areas of erosion (BOUMA et al. 2007).

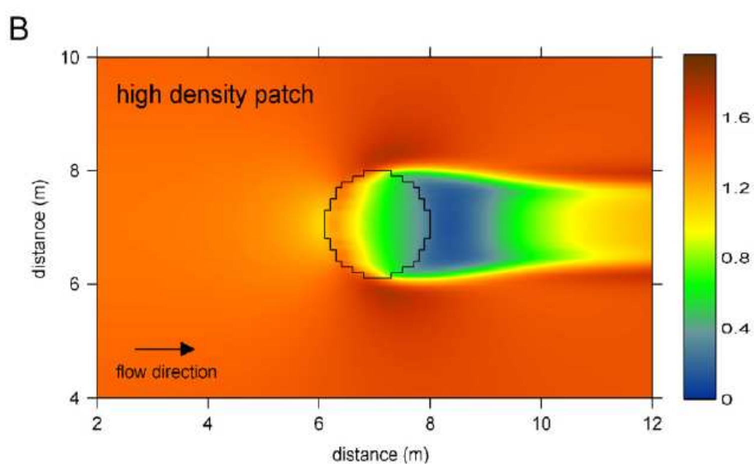


Fig. 4.10 Modelled bottom shear stress [N m⁻²] with Delft- 3D at a high density bamboo patch (BOUMA et al. 2007)

Another flume experiment of BOUMA et al. 2009 addresses the vegetation density of real Spartina anglica and its effect on hydrodynamics. It is found that stem density has a significant effect on flow reduction and depth of scouring next to the vegetation.

Other experiments in the flume with real Spartina anglica plants also show overall reduced turbulence and velocities within the vegetation but a high turbulence zone at the front (first 50 cm) of the vegetation in the flume for submerged vegetation.
For partially emerged vegetation no reduction of flow velocity was found and the turbulence is much higher than in submerged vegetation. Turbulence can reduce sediment settling or cause erosion under extreme conditions (NEUMEIER 2007).

Turbulence and Reynolds' stress

Turbulences are 3D eddy motions in a steady and uniform flow. While the mean flow is constant in x direction the instantaneous fluctuation (u'), called turbulence, from this mean is changing in direction and time. Over a longer time this fluctuation of u' must be zero, but to quantify the **turbulent intensity** the root mean square of u' is given.
These fluctuations have acceleration gradients in space and are called **Reynolds' stresses** if they are multiplied by mass per unit fluid volume.
The **TKE** gives the mean kinetic energy per unit mass characterised by turbulent fluctuations
(LEEDER and PEREZ-ARLUCEA 2006).

4.4.4 Spartina tussocks and landscape effects

The impact of vegetation on landforms is a big part of biogeomorphology whereas the different time spans in which vegetation and geomorphology changes create difficulties in predicting landform- vegetation interactions (PHILLIPS 1995).

Also Spartina tussocks in a dynamic tidal environment have off- site effects on a larger scale and hence can cause changes on a landscape scale.

TEMMERMAN et al. 2007 describes channel formation on a tidal flat due to coalescence of Spartina tussocks colonising a mudflat.

Fig. 4.11 shows that distinct channel formation starts in 1996 with increasing vegetation density.

A modelling approach describes this process and gives a similar result as observed on the aerial photographs.

The model starts with a homogeneous flow field, when vegetation patches start to develop the model reduces current velocities and bed shear stress within and behind the patches and enhances these parameters between the patches. If the patches grow together the bed shear stress between patches reaches a threshold, where channel erosion starts to take place. The model is assuming that at this point patches stop to expand when a channel is present.

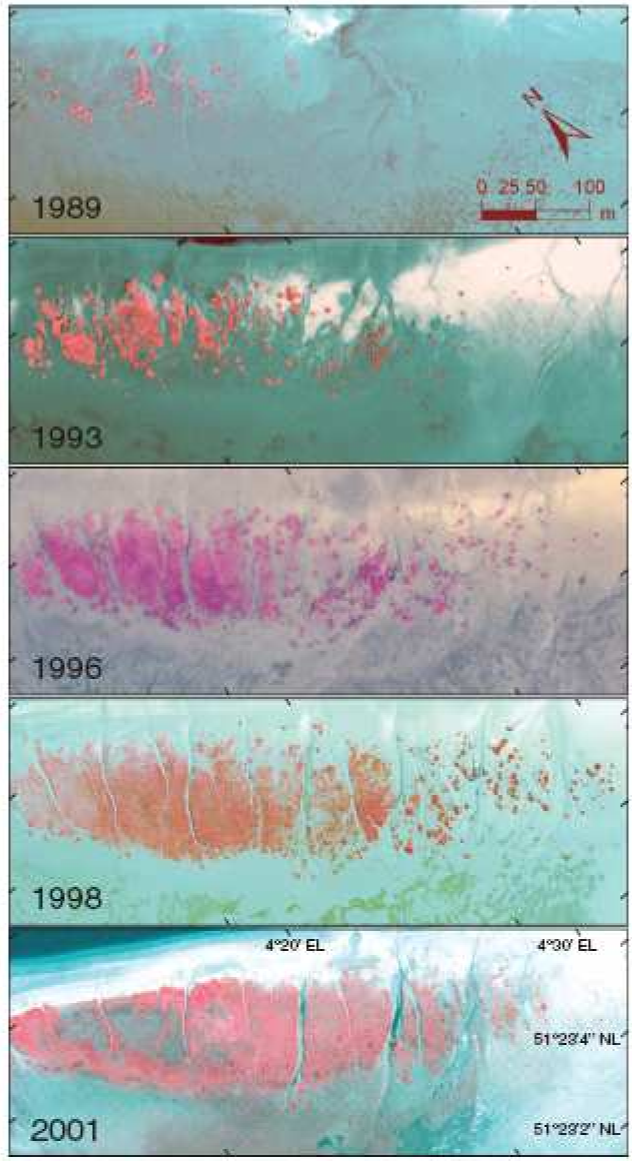


Fig. 4.11 Aerial photos of Plaat van Valkenisse describing channel formation with increasing tussock density (TEMMERMAN et al. 2007)

In contrast to publications which report that topography is the main reason in forming tidal channels, this study shows that vegetation is able to have large scale effects and can explain tidal channel formation. This could also explain, why “the geometric properties of channel networks in tidal marshes are not scale invariant” like in terrestrial networks (TEMMERMAN et al. 2007).

5 Study sites

5.1 The Westerschelde estuary

5.1.1 Geography of the Westerschelde

The river Schelde is about 350km long, has a catchment area of 21860m² and a mean runoff of 120 m³ /s varying with the seasons (SCHELDE INFORMATIE CENTRUM 1999).

Only the part below the harbours of Antwerp is called the Westerschelde whereas the upper parts are called Zeeschelde and Boven Schelde (Fig. 5.1). The tidal influence reaches 160 km inland and is meso- to macrotidal with 2.26m - 4.46m at the North Sea, 4.49m - 5.93m at Schelle and 1.84m - 2.24m at Ghent. The part with tidal influence is defined as the Schelde estuary. The suspended sediment of riverine and marine origin consists of fine sands to clay with extreme variation in space and time.

The Westerschelde is a flood and ebb channel dominated multiple stream with tidal mud and sand flats. The eastern part of the Westerschelde, from the east side of Plaat van Ossenisse onwards, is brackisch (TEMMERMAN 2003).

The Westerschelde is a modern shipping area connecting the harbour of Antwerp with the North Sea, a third dredging project is currently ongoing (2007-2009) to deepen the channel for ships with 13.1 m draught.

16000 Sea going vessels reached the harbour of Antwerp 2007, significantly more ships are cruising on the Westerschelde in total reaching e.g. Vlissingen and Terneuzen (PORT OF ANTWERP 2009).

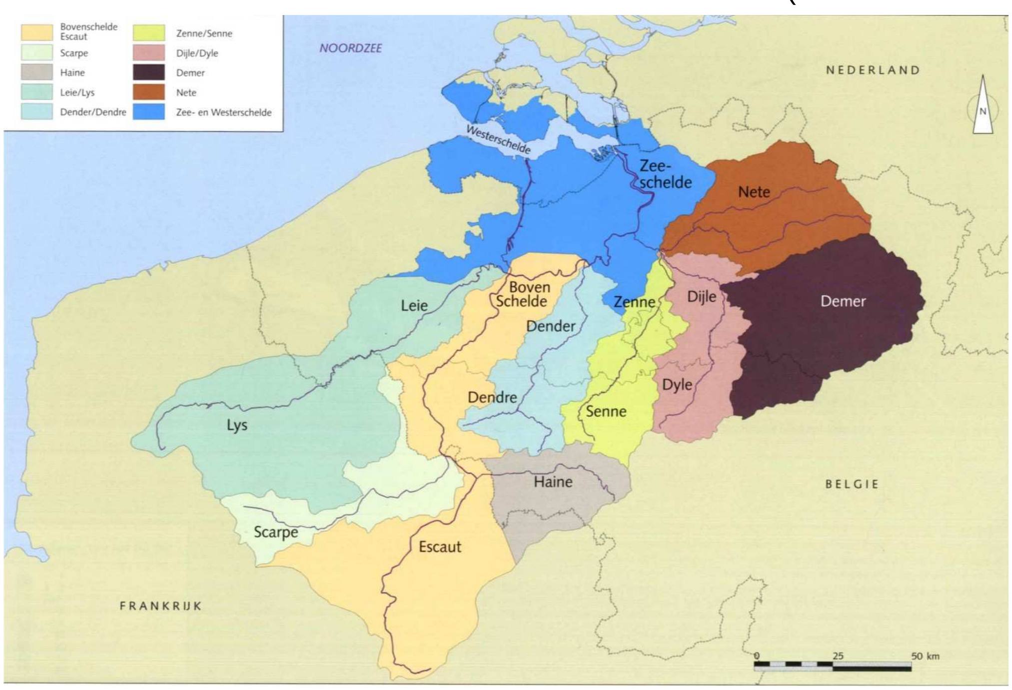


Fig. 5.1 Catchment area of the Schelde (SCHELDE INFORMATIE CENTRUM 1999)

5.1.2 Dynamic Westerschelde

Fluvial and marine processes formed the estuary of the river Schelde which has only become stable in its contours because humans started to build dykes and groynes.

Sea level rise and storm surges always pushed the shoreline back inland whereas peat and sediment accumulation let the shoreline proceed seawards. The rivers had to find their way into the sea and were always following different pathways during the course of history.

In the 10th century people settled again after a period when Zeeland was uninhabitable and built small dykes to protect their land from flooding. Especially in the 19th century, when the "Kreekrak" has been closed and the "Sloedam" was built, the Westerschelde was closed off from the Oosterschelde and squeezed into its present shape (SCHELDE INFORMATIE CENTRUM 1999).

This process is also called "coastal squeeze" and describes especially the habitat loss due to embankment because natural dynamics of the shoreline are stopped (DOODY 2008).

The ebb and flood channel structure of the Westerschelde is stable in most places since 1930 but this equilibrium is changing continuously.

Between 1980 and 2002 the area of the tidal flats especially in the western parts was decreasing due to changes of the connecting channels. Dredging and dumping of sediment is likely to change the dynamics significantly (KUJPER et al. 2004).

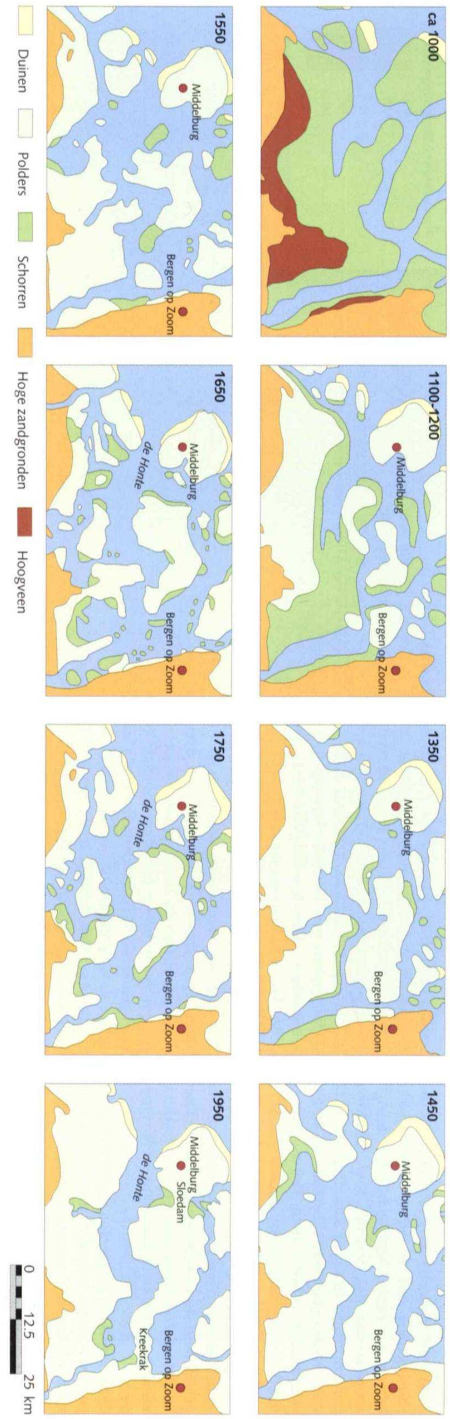


Fig. 5.2 History of the Westerschelde (SCHELDE INFORMATIE CENTRUM 1999)

5.2 The Blackwater estuary

The Blackwater estuary is located in Essex in SE England and is defined as the last 23km of the River Blackwater. The tidal range at the Essex coast is in average 4.5m. 498ha of salt marshes were situated in this estuary in 1998 (VAN DER WAL and PYE 2004, CHANG et al. 2001).

The fieldwork was done at a managed realignment site within the Blackwater estuary.

This restoration site of Tollesbury is part of the Tollesbury and Old Hall marshes at the NE part of the Blackwater estuary.

More than 150 years ago 21 ha of marshland have been embanked for agricultural use, in August 1995 the plans to restore this marshland and reconnect it to the tidal influence became reality, a 40 m wide dyke breach was made.

Since then 70 % of the site is flooded during MHWN whereas the whole site is covered during MHWS, the semidiurnal tidal range is about 4.5m.

The managed realignment site is now directly connected to the Tollesbury Creek (Fig. 8.19) and a new seawall was built to defend floods (WATTS in DEFRA 2008).

5.3 The German Wadden Sea

The Wadden Sea of Schleswig-Holstein is located north of the Elbe estuary at the German westcoast (see Fig. 6.1). A national park (Schleswig-Holsteinisches Wattenmeer) of 440,000ha was founded in 1985 which is the biggest in Germany.

11,600 ha of salt marsh form the westcoast of Schleswig-Holstein whereas 8,400 ha are situated at the mainland.

Nearly every salt marsh at the westcoast has been in agricultural use in the 1990th and the pioneerzone is mostly dominated by sedimentation fields (German: Lahnungen). More than 70% of the salt marshes were formed due to the presence of those sedimentation fields. Also the drainage of most of the salt marshes follows man made ditches (German: Grueppen). About 50% of the mainland salt marshes within the national park are still intensively (15%) or extensively (39%) grazed the other 50% are out of use, maintenance of the sedimentation fields and ditches and grazing has stopped (STOCK et al. 2005).

6 Fieldwork

6.1 Overview

To make a clear statement about principals of biogeomorphological processes it is beneficial to compare between contrasting sites. The Westerschelde is naturally a highly dynamic environment with a high human impact on sediment- and hydrodynamics. The inhomogeneity enables to choose spots with contrasting physical and biological conditions along the estuary, but dredging, dumping, shipping and recreational use can disturb the natural circumstances and can lead to false conclusions. The dumping of big volumes of sediment on a particular spot for example can change the whole sedimentation process in no time.

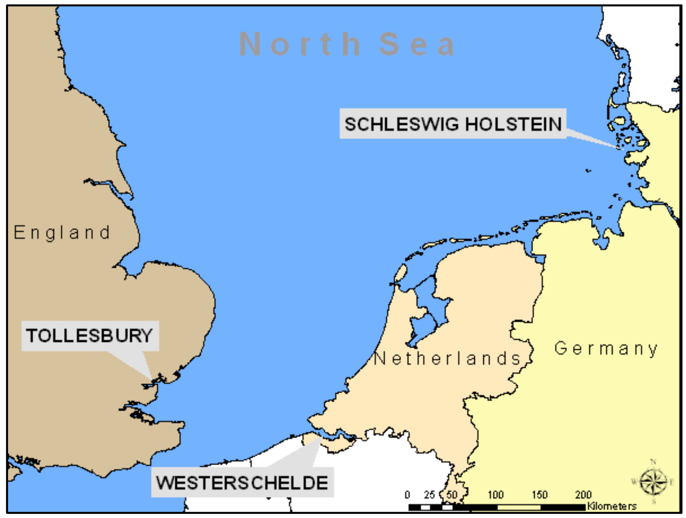


Fig. 6.1 Three fieldsites in Europe: Tollesbury as a part of the Blackwater estuary, Westerschelde in the SW Netherlands, Wadden Sea of Schleswig- Holstein in Germany

To get a clear comparison to this environment, a restoration site in the UK has been chosen to perform DGPS measurements. This restoration site was founded with a wilful dyke breach about 14 years ago and accreted since that time, furthermore the small inlet of this new marsh dampens hydrodynamic forcing.

For further insight in the varieties of Spartina tussocks a visit to the German Wadden Sea of Schleswig-Holstein has been realised, whereas no measurements have been done.

6.2 Fieldwork methods

6.2.1 Choosing DGPS as a survey method

There are several methods ranging from manual measurements to high tech methods to determine the relative and absolute height or in general the topography of a surface. REYBURG et al. 2008 compares the different methods of airborne laser altimetry LiDAR (Light Detection And Ranging) and DGPS ground based survey, whereas LiDAR is more effective on a landscape scale than the labour intensive DGPS ground survey.

For the measurement of 1-100 m² big tussocks however the resolution of LiDAR is not high enough, moreover LiDAR is not able to penetrate vegetation and water, which stays for example in the gullies.

Therefore a small scale solution had to be found. The most precise and accurate small scale height measurement is done by a laser level instrument, but to determine the x and y position of the measuring staff, which would be needed to cover the surface, a lot manual work needs to be done. This method is only useful to give the exact height of a few points.

With an installation of a frame around the tussock a levelling staff could be used to measure exact heights to a relative point within a certain grid, but this method is not suitable as a mobile solution. Both methods have already been used to determine dome height and gully depth of tussocks (VAN WESENBEECK et al. 2008 and BOUMA et al. 2007, WARD et al. 2003).

Nowadays it is possible to scan a surface with sub centimetre accurate 3D laser scanner. But spatial imaging is not possible within vegetation and through water.

Therefore the only suitable mobile solution to generate a grid of height measurements around and within tussocks is a differential GPS, which allows to determine heights with centimetre accuracy and which is a flexible solution to measure many points (see Fig. 6.2). Because of micro relief like gullies, creeks and small cliffs no fixed grid for measuring points was used but a flexible method to map the contours of the topography. This led to an average measuring point density from 12 points per m² for tussocks with a complex topography to 4 points per m² for smooth and simple surfaces (see Fig. 6.3).

Fig. 6.2 Fieldwork with DGPS Rover at Plaat van Walsoorden

It is possible to measure every creek and gully if needed and additional information can be stored within the xyz file to map features like position of sediment samples, vegetation and so on.

The tussocks have been chosen in the field, whereas different criteria where important: (1) no or low influence of other adjacent vegetation or structures, (2) single tussocks which have not been visibly merged together, (2) representative for adjacent tussocks.

These criteria have been used to make sure that only the tussock itself and the physical environment is influencing its topography.

Fig. 6.3 shows how the measuring points spread over the area.

Because with the following interpolation of the heights sharp edges get softened they are indicated as micro cliffs as they have big importance in terms of indicating erosion.

The processing of the DGPS data is described in chapter 7.1.2.

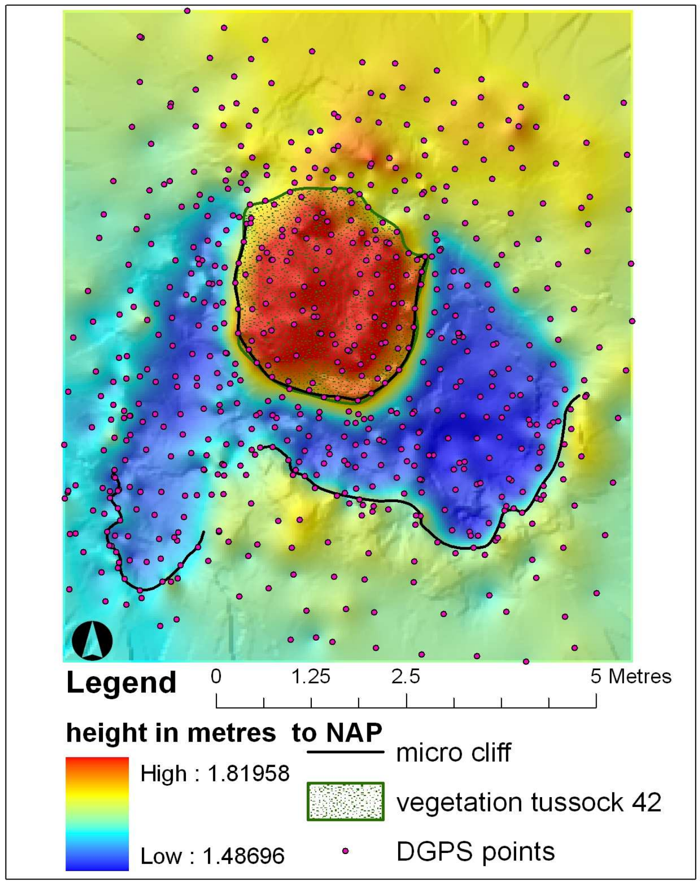


Fig. 6.3 Example of a tussock DEM (No 42) with 640 measuring points. Interpolated surface with hillshade effect made with ArcVIEW 9.3.

6.2.2 How does DGPS work?

Since the 1960th satellite navigation systems were developed, meant for military purposes first and than becoming available for civil use. The first and still commonly used US GPS system NAVSTAR consists of 24 satellites whereas at least 4 satellites are needed to give the 3D position of a GPS user on the earth. Other fast developing systems are GLONASS (Russian) and GALILEO (European) which all together are now known as GNSS (Global Navigation Satellite System).

The GPS user receives exact time signals from each satellite and can calculate his position with the difference of each time signal.

Due to several sources of error, which can delay or lengthen the pass of the GPS signal, the absolute accuracy of the determination of position is better than 13m horizontal and better than 22m vertical.

Sources of error are the reflection of the GPS signal on nearby structures and surfaces e.g. mountains or water surface, known as the multipath effect, reflection and diffusion of the signal in the ionosphere and troposphere and shadowing effects of e.g. buildings which lead to a poor visibility of satellites.

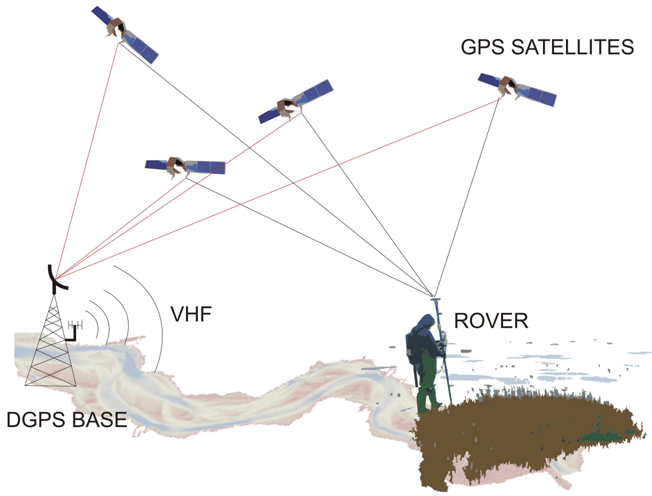


Fig. 6.4 Scheme of DGPS measurements. The Rover is receiving the correction signal from the base station.

In Europe they developed a system to achieve better accuracy called EGNOS (European Geostationary Navigation Overlay Service), it consists of 34 reference stations in Europe. These reference stations have known positions and can therefore estimate the errors of the atmosphere and ionosphere and send this correction signal via the satellite (WAD = Wide Area Differential) to the user, it can improve the absolute accuracy to better than 2m horizontal and 5m vertical (KAHMEN 2006).

A DGPS is working with the same principle on a smaller scale. “A DGPS system employs a local reference station, which has a high-quality GPS receiver at a known surveyed location. The reference station estimates the slowly varying error components of each GPS satellite range measurement and forms a scalar correction for each GPS satellite in view” (KRAMER 2002).

Whereas EGNOS is a large scale correction system sending his data via the GPS signal, a DPGS is a local system within visual range of the user which is sending his correction signal in realtime (RTK = Real Time Kinematic) on a local pathway via radio signals (UHF or VHF frequencies) or mobile phone connection (GSM).

The receiver of the GPS user is called “rover” and the reference station, base station (Fig. 6.4).

The absolute accuracy of the determination of the position is always better than 1cm horizontal and 2 cm vertical depending on the distance to the base station and the local system which is used. To minimize the distance effect the provider uses models to determine the error for each position within the reach of the base station, therefore the

GPS rover has to send his approximate position to the base station to receive his personal correction signal.

Because the errors change only slowly within time and local multipath errors stay the same at one spot, the relative precision of measurements within a short time range is higher than the absolute accuracy (Fig. 6.5) (KAHMEN 2006).

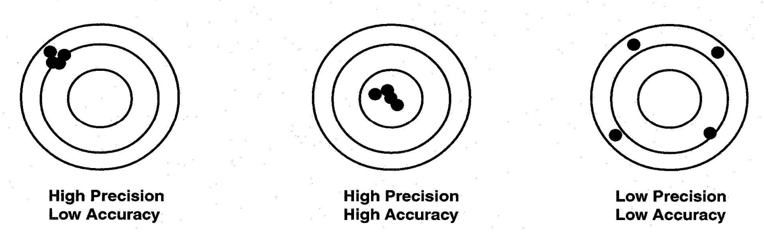


Fig. 6.5 Accuracy and precision **(http://cehd.umn.edu)**

Especially on a mudflat the visibility of satellites is very good once you are several meters away from the dyke and only reflections on the water surface can cause some problems. The absolute accuracy during the fieldwork was always better than 1cm horizontal and 2 cm vertical, however the precision, which is more important for this work, is expected to be significantly higher without knowing exact figures.

In the Netherlands a VHF connection was used provided by THALES/MAGELAN whereas in the UK a GSM connection to the VRS (Virtual Reference Station) system of Trimble was used.

6.2.3 Sediment and vegetation

Beside the topography it is interesting to know the details about grain size and bulk density to relate it to hydrodynamics and impact of vegetation presence.

Therefore a volume of 19cm³ has been sampled from the top 3 cm of the surface with a plastic tube. This tube was made of a 60 ml syringe of which the tip has been cut off. The sediment has been stored in sample jars and processed in the laboratory as soon as possible (see chapter 7). The samples where taken in the centre of the vegetated patch, in the front right corner of the measured grid looking towards the upcoming flow direction as a reference sample and behind the patch if a distinct wake zone was present. Different photos have been taken of each tussock and observations have been noted. To describe the appearance of the tussock vegetation, the average stem height has been metered and the number of stems within a 20 cm x 20cm frame has been counted to determine the stem density. The time of year has to be taken into account by analysing this data, because some stems at exposed sites already might have been damaged after the growing season, but in general on most places the stems stay in a good shape throughout the winter (NEHRING and HESSE 2008).

6.3 *Fieldwork along the Westerschelde estuary*

Seven contrasting locations have been chosen along the Westerschelde estuary.

Fig. 6.6 shows the three tidal flats (shoals) Hooge Springer, which is a part of Hooge Plaate, Plaat van Baarland just in front of the Baarland salt marsh, and Plaat van Walsoorden close to the Verdronken Land van Saeftinghe. Moreover four mainland marshes have been chosen which are Hoofdplaat, Paulinapoler, Zuidgors and Baarland. Plaat van Walsoorden is located in the brackish part of the estuary (TEMMERMAN et al. 2003).

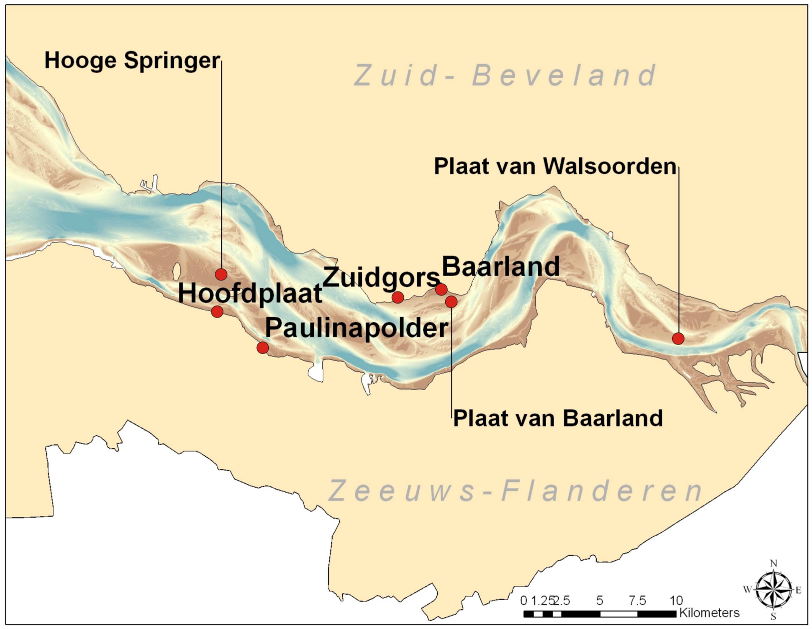


Fig. 6.6 Fieldwork along the Westerschelde estuary. 3 tidal flats called 'platen' (with lines) and 4 salt marshes.

All tidal flats and marshes show patchy Spartina anglica vegetation in a different way, are situated in the reach of the DGPS correction signal and for all sites aerial photographs are available, these are the main criteria to perform this kind of fieldwork.

All the salt marshes can be reached by foot whereas the fieldwork on the tidal flats required a boat to get there during low tide.

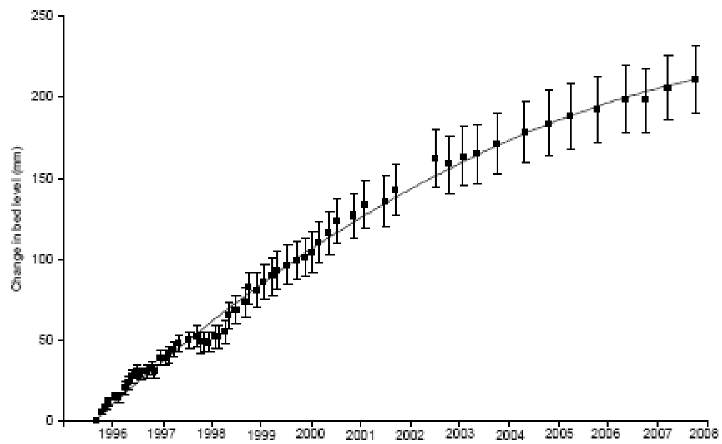
The fieldwork was done between the 24^{th} of October 2008 and 7^{th} of November 2008 on the salt marshes and from 17^{th} of October 2008 until 19^{th} of October 2008 on the tidal flats.

The spatially wide spread fieldwork makes it possible to compare different tussocks at different sites and give a good overview of the variety of tussock shapes, the short time span of the measurements guarantees a comparable situation.

In the addendum the development of the area around the tussocks between 2004 and 2008 is shown, see chapter 8.1 for the physical state of the locations.

6.4 *Fieldwork at the managed realignment site of Tollesbury*

Since the dyke breach sediment at Tollesbury is accreting with a rate of 30 mm/year in average at the beginning and 9.6 mm/year in recent times (See Fig. 6.7) The DEFRA (Department for Environment, Food and Rural Affairs) together with the ITE (Institute for Terrestrial Ecology) and the CEH (Centre for Ecology and Hydrology) with the help of several research institutes monitored this site since its start. Extensive data about invertebrate colonisation, vegetation monitoring, sediment accretion and soil studies are available. These are perfect conditions to study the biogeomorphology of Spartina anglica tussocks within a controlled and monitored environment. 22 Tussocks (see Fig. 8.19) have been measured at Tollesbury in January 2009. Sediment samples were taken within and in front of the tussock.



6.7 Accretion at the Tollesbury restoration site since the dyke breach. Starting with 30mm/year in the beginning. (GARBUTT in DEFRA 2008)

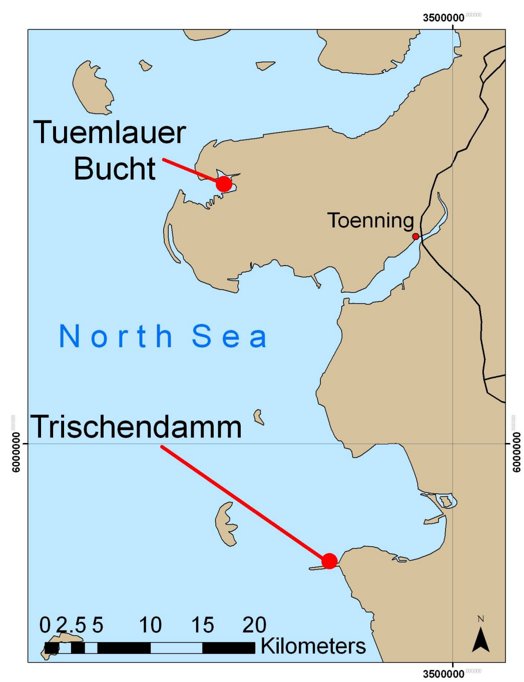


Fig. 6.8 Fieldsites at the German Wadden Sea of Schleswig-Holstein. Tuemlauer Bucht near Westerhever and North side of the Trischendamm near Friedrichskoog.

6.5 *Fieldtrip to the German Wadden Sea*

A short trip to the German Wadden Sea of Schleswig-Holstein in January 2009 helped to gain further insight into the variety of Spartina anglica tussock topography.

After visiting 5 different salt marshes 2 appeared to be interesting because of their regular patterns, Tuemlauer Bucht and Trischendamm (Fig. 6.8).

The man made sedimentation fields along the coast and the different processes at the Wadden Sea made it worth while to make a qualitative comparison to the Westerschelde tussocks. Aerial photographs supported the visits to the fieldsites.

7 Data processing

7.1 GIS analysis

7.1.1 Analysing D-GPS measurements

The measured points in the field were imported in ArcView 9.3 via an ascii file.

All mapped observation points, vegetation area, micro cliffs and other observations e.g. dead spartina stems, were transformed into polygon and line features (Feature Data Set) within a Personal Geodatabase. This has the advantage that the area of each polygon is given without further analysis and that the database can be modified in MS Access. Every tussock has its own number to refer to it. To create a Digital Elevation Model (DEM) from xyz points ArcView provides several methods of interpolation. Interpolation allows us to create a continuous surface from distinct values, in this case elevation. The DEM is a raster dataset characterised by its cell size which is depending on the density of the measuring points. The interpolation methods ArcView 9.3 provides are:

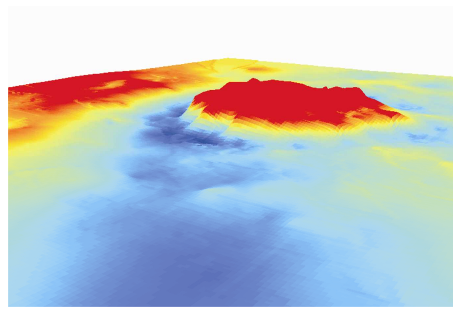


Fig. 7.1 3D view of interpolated DGPS measurements (tussock 52)

a) Inverse Distance Weighted (IDW)

The IDW is a weighted distance average and can not be higher or lower than the maximum or minimum of the measured points. “Therefore, it cannot create ridges or valleys if these extremes have not already been sampled”. Errors occur for sparse or uneven distribution of measuring points (ArcVIEW 9.3 Desktop help).

b) Natural Neighbour

This method is best used for large data sets. “It finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas in order to interpolate a value” Like IDW it does not represent ridges or valleys if not measured.
The smooth surface output is interrupted at the input points (ArcVIEW 9.3 Desktop help).

c) Spline

The Spline method creates a smooth surface exactly through the measured heights.
If you have different heights adjacent to each other due to measuring errors, this method fails (ArcVIEW 9.3 Desktop help).

d) Kriging

"Kriging is an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with z-values." In contrast IDW and Spline are only a deterministic method.
Kriging is similar to the IDW method but the weights are not only based on the distance between the points, but also on the overall spatial arrangement of the points.
Using a geostatistical model Kriging is a processor-intensive multistep process.
The default setting in ArcVIEW 9.3 is the ordinary Kriging method with a spherical semivariogramm model (ArcVIEW 9.3 Desktop help).

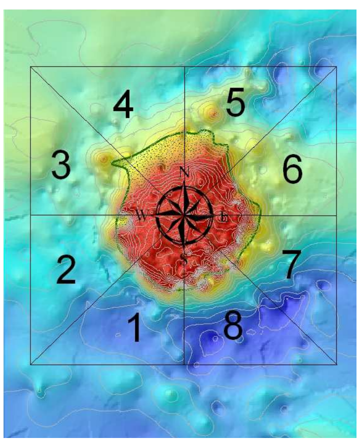
To produce the DEMs of the tussocks the Kriging method with default settings is used because it is the most advanced interpolation method which can process uneven distributed values and gives a realistic picture of the measured surface (Fig. 7.1). Also the cellsize is set as default (the shorter of the width or height of the input features divided by 250).
The maps showing the DEM of the tussock also show the vegetation area in green and the micro cliffs with black lines. To get a 3D impression the hillshade tool was used.
Every interpolated DEM can be opened and viewed with ArcVIEW from the Data CD at the end of this thesis.

7.1.2 Analysis of tussock topography

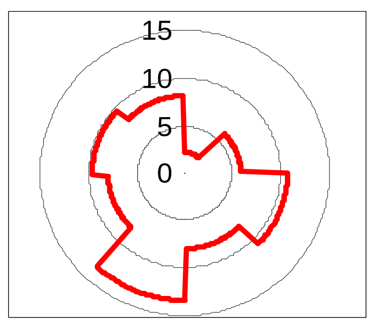
Based on this DEM nearly every parameter of the tussock topography can be analysed. To determine parameters which show patterns of tussock topography, simple comparable numbers for each tussock and important features which are considered to influence growth rates the following analysis were done:

a) North orientated slope slices

To show patterns of tussock topography the slope of the tussock edge is an interesting factor. Therefore the maximum slope of each of the eight pie slices has been analysed.
The big variety of tussock topography and inhomogeneity of the surface made it impossible to use the slope toolbox in ArcVIEW because it gives solely the slope of each raster cell to the other.
The only possibility to do this is a rather manual method by creating contour lines of the DEM and measure the slope along the steepest gradient from inside the tussock to where the slope stops outside the tussock. If the tussock height is lower than its surrounding the slope is defined as negative.
For spatial patterns of tussock slopes only elevated tussocks, which can have a steepest gradient in a certain direction because of main flow direction or wave attack, are of interest. If negative slope slices occur at an elevated tussock the number given in the diagram (Fig. 7.2) is zero. If there is a micro cliff at the edge of the tussock every slope is automatically set as 90 degrees. For better visualisation 90 degrees slopes are shown in the diagram as those slopes who reach the outer ring of the diagram.



Slope pie slices of a tussock



Slope diagram in degrees, north- orientated

Fig. 7.2 Producing north orientated slope pie slices of tussocks. First the slope of each slice at the vegetation edge is measured with GIS and then plotted in Excel.

b) Volume analysis

The biggest advantage and the biggest challenge of this approach is to estimate the volume of the tussocks.

To guarantee comparability and faster processing of the data ArcGIS Model Builder was used to calculate volumes (Fig. 7.3). As an input the point dataset of the measurements, the polygon of the tussock vegetation and the interpolated Tussock DEM is needed.

Moreover you have to set how big the buffer around the tussock will be.

To calculate a volume of a tussock it is necessary to decide what kind of height reference you want to use and which surface area.

Therefore two different approaches exist answering to different questions.

To estimate the volume of tussock and gully a distance of 1m around the tussock has been chosen as the outer limit of the calculation. The reference plane was calculated by trend interpolation of all measured points within and outside the tussock (Fig. 7.4).

Afterwards the trend interpolation is subtracted from the tussock DEM.

The output is a text file in which the positive volume and the negative volume to the trend interpolation of the area of the tussock and 1m around it is given. This method was used for all tussocks of the Westerschelde to estimate the net topography effect of the tussock (Fig. 7.4) i.e. the net volume.

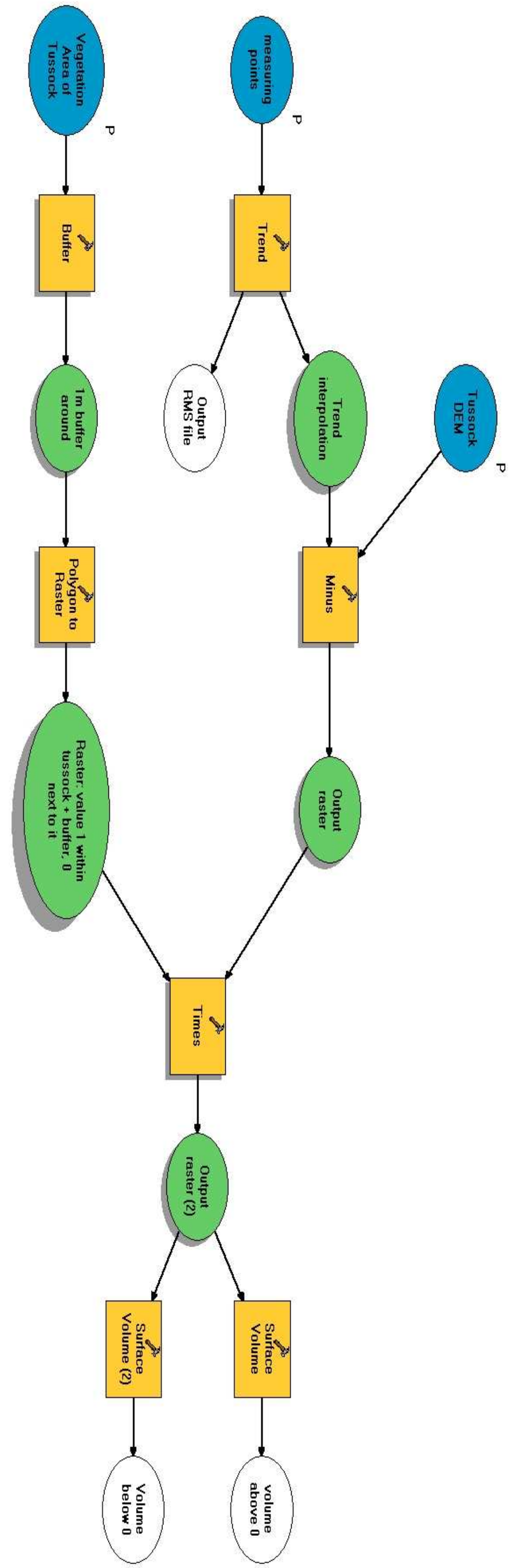


Fig. 7.3 Volume calculation with ArcGIS model builder. The output gives the positive and negative volume to a reference plane.

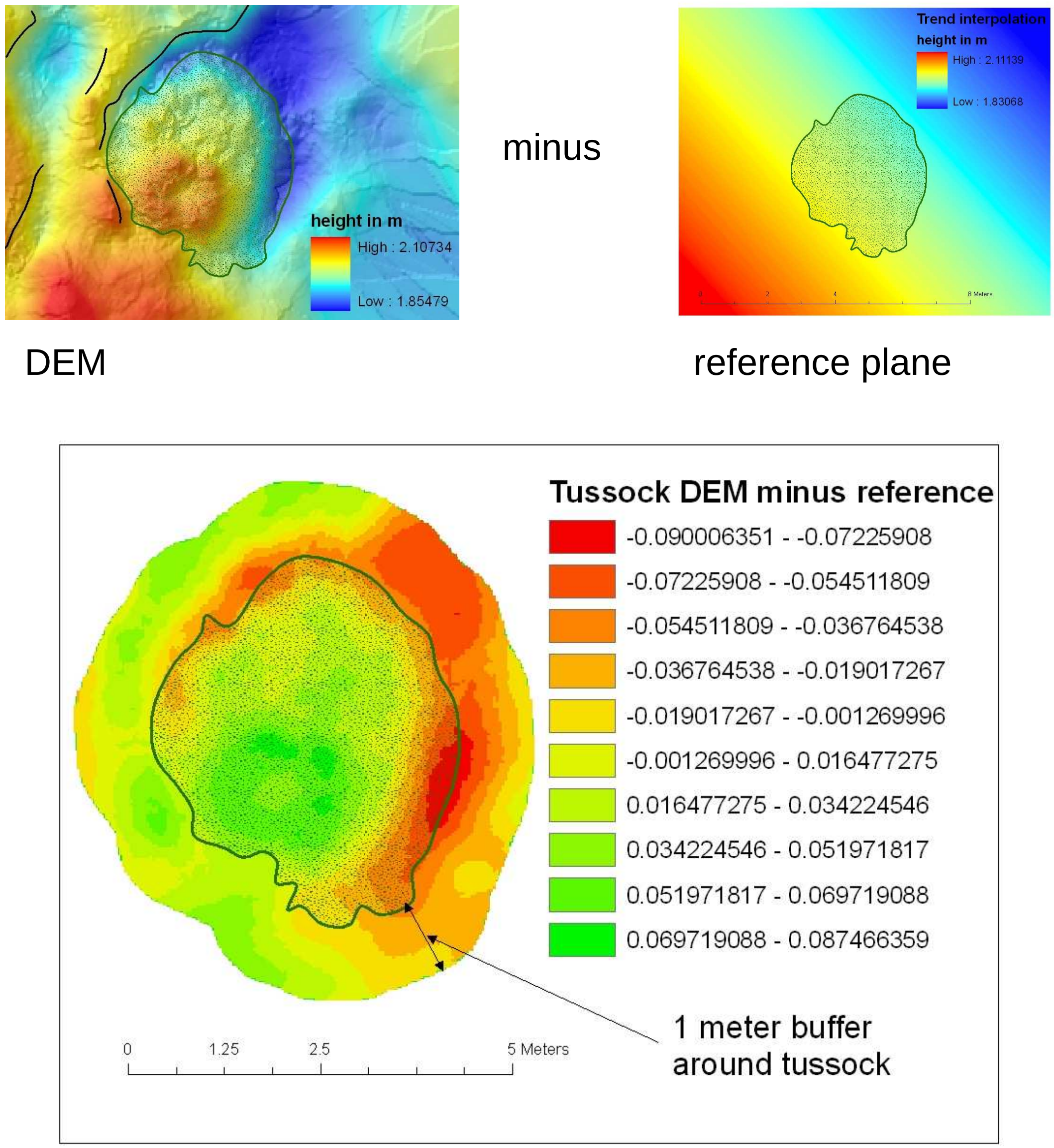


Fig. 7.4 Volume of tussock and gully to reference, 1m buffer scenario

There is a similar way of analysing the precise volume of all dome shaped tussocks of the Westerschelde and the tussocks at Tollesbury.

The buffer around the tussock, which determines the area of the volume analysis, is set to 1mm (for modelling reasons not 0) to just look at the tussock vegetation.

The points which are used for the trend interpolation of the reference plane consist of all measurement points outside the tussock to exclude the greater heights of the elevated tussock. This has not been done for the 1m buffer scenario because also tussocks in a depression and flat tussocks have been analysed and to guarantee a comparable method for all tussocks.

c) height analysis and area

For the height analysis it is also important to define a reference and therefore the same reference plane as for the volume analysis is used.
For all tussocks of the Westerschelde the output raster of the volume analysis model (Fig. 7.4, 1m buffer) gives the maximum height differences between tussock and reference plane and gully and reference plane. Tussocks in a depression and gullies have a negative value whereas elevated tussocks have a positive number.
Also for Tollesbury the maximum height difference of the tussocks to the reference plane was determined with the volume model output as described above.
The area of each tussock is directly given in the attribute table of the polygon feature dataset.

7.1.3 Categorisation of tussocks

Already in the field it gets clear that there are differences between individual Spartina anglica tussocks. Some tussocks are clearly elevated resulting in a dome shape others are forming a depression, some seem to remain totally flat and seem to follow the topography of its surrounding, others look elevated in the front but are level at the back of the tussock which can be described as a terrace. Elevated tussocks can also have a micro cliff most likely at the seaward side.

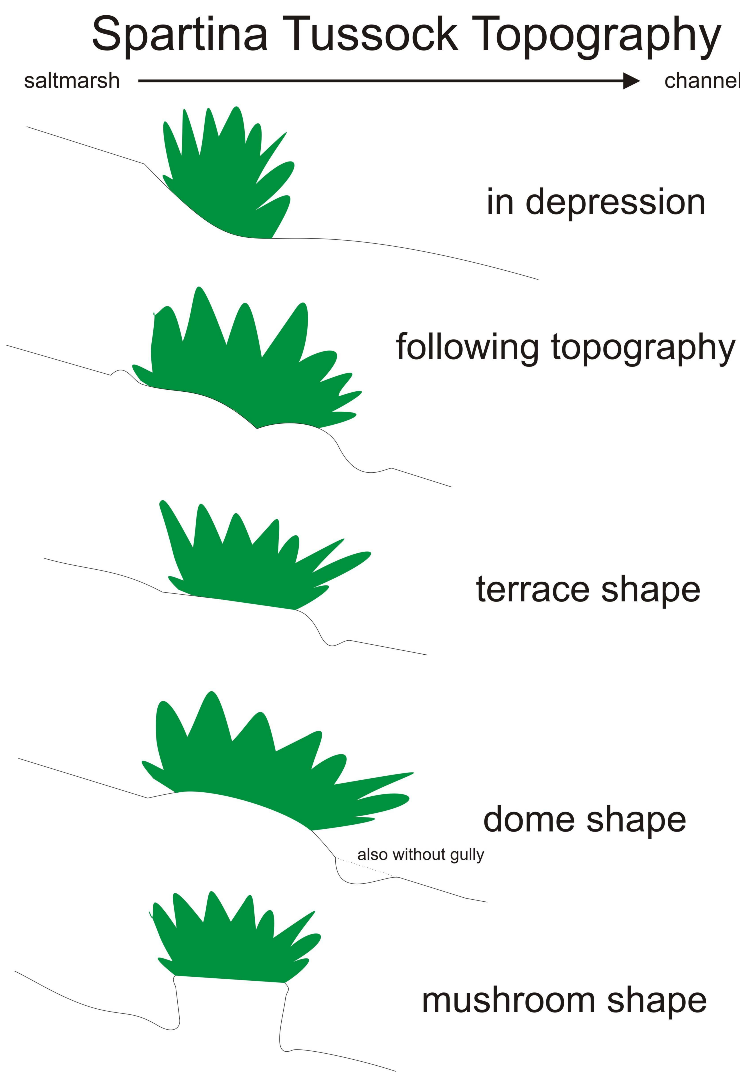


Fig. 7.5 Tussock categorisation with different topography based on field observation and DEM analysis

Most striking are those tussocks who stick several tens of cm out of the landscape with undercut edges. The remaining roots hang loose at the sides and therefore this formation looks like a mushroom. Fig. 7.6 shows a mushroom shaped tussock at Hooge Springer. All mushroom shaped tussocks are accompanied by gullies around the elevated hummock.

Fig. 7.6 Mushroom shaped tussock at Hooge Springer with deep gully

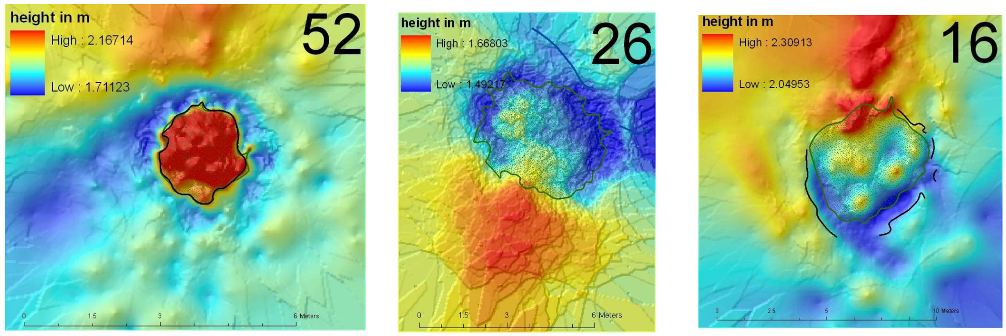
classification	8 slope slices in degrees
in depression	all < 0°
topography	all = +/- 0°
terrace	front > 0°; back <= 0
dome	all > 0°; all < 90
dome with cliff	>=2 slices = 90° and <=7 slices = 90°
mushroom	all = 90°

Fig. 7.7 Tussock shape classification with the 8 slope slices of the vegetation edge

To quantify this obvious categorisation of the topography it is possible to use the slope slices described in chapter 7.1.2 a.

Tussocks in a **depression** have negative slopes all around, tussocks following the **topography** have only very small slopes close to 0. The slopes of **dome** shaped tussocks are all positive but not 90° whereas **mushroom** shaped tussocks have only 90° slopes. For **terrace** shaped tussocks slopes facing the seaward side are positive, whereas slopes in the back are negative or zero. For elevated tussocks with a **cliff** it is defined, that at least 2 but not more than 7 slope slices of the tussock have 90°.

Next to the tussock itself the surrounding gullies can also be categorised in a descriptive way. The gullies can be O, U or Y shaped, meaning that they are located all around the tussock (O) or in the front and at both sides (U) or at the sides with an outlet (Y). However, most tussocks do not have a distinct gully formation or only local scouring in the front.



O shaped U shaped Y shaped

Fig. 7.8 Gully categorisation of tussocks with distinct gullies

7.1.4 Analysing available GIS data of the Westerschelde

Airborne laser altimetry data of the Westerschelde provided by the Directorate General of Public Works and Water Management (Rijkswaterstaat, RWS) is available for 2001 and 2004, although new laser scans have already been done, the new data is not yet available.

The 2001 data has a 5m spatial resolution whereas the 2004 data has a 2m resolution, both with a minimum vertical accuracy of 20cm (VAN DER WAL et al. 2007; TEMMERMAN et al. 2004).

More recent data of the sediment dynamics of the Westerschelde is receivable in form of manually measured transects across the tidal flats also done by Rijkswaterstaat (RWS).

This data is available for all fieldsites except Hoofdplaat but the transects are not always in direct vicinity of the measured tussocks, in that perspective it has a big disadvantage to the laser altimetry, the only possibility to link each measured tussock to gross accretion or erosion of the tidal flat around.

By using the Raster Calculator in ArcVIEW 9.3 the 2001 altimetry is subtracted from the 2004 altimetry to show a trend in erosion or accretion.

Furthermore the output of this calculation is intersected with the shape files of the 61 tussocks to get a trend of the surrounding of each tussock between 2001 and 2004.

Because this data is rather old but the only available for each tussock the sediment transects were used to validate this data. The transects reveal if the trend which was observed in those years has been continuing until now, see more in chapter 8.1.

7.1.5 Analysis of aerial photographs

Sequential false colour aerial photographs, also provided by Rijkswaterstaat, are available for all fieldsites at the estuary. Because the photographs have already been used for research (VAN DER WAL et al. 2007) precise geocorrection was done for pictures between 1982 and 2004. The 2008 pictures are geocorrected as they have been taken. Photos are available for 08/1982, 06/1993, 07/1998, 08/2004, 08/2008.

To estimate growth rates of each tussock the 2004 aerial photos were used to produce shape files of the 2004 size of each measured tussock.

7.1.6 Tussock growth rates

By comparing the tussock polygons of 2004 and the measured tussocks of 2008 a growth rate in m² can be calculated.

Because this is depending on the size of the tussock a lateral growth rate in cm/year is needed. Therefore for each tussock area (A) its theoretical radius (r) is calculated and hence the lateral growth rate in cm/ year.

$$A_{(tussock)} = \pi * r^2$$

7.2 Sediment samples

The sediment samples were taken to the laboratory as soon as possible after they had been collected. They were freeze- dried for 3 days and weighed afterwards. The bulk density is given in g/cm³ of freeze dried sediment to the volume sampled in the field. The samples were dry sieved (< 1mm sieve) prior to the grain size analysis with a laser particle size analyser (Malvern Mastersizer 2000).

The Malvern analysis was done by the laboratory staff of the NIOO-CEME.

A sub-sample of the sediment is taken and dispersion is achieved with supersonic.

A treatment with hydrogen peroxide is not common at this laboratory.

The median grain size of the sample is the most important number next to clay/silt/sand content in percentage.

Fractions smaller than 2µm are called clay, between 2 and 63µm silt, and between 63 and 2000µm sand, whereas grains up to 200µm are still within the fine sand fraction (AG BODEN 2005).

If the samples do not contain clay, a median grain size below 63 µm means that the sediment consists more than 50% of silt, if it is bigger than 62 µm it consists more than 50% of sand.

8 Results and discussion

8.1 Site comparison

To reveal patterns in tussock topography a site comparison is most reasonable because already in the field differences were obvious.

In the following paragraph the tussock patterns at all sites are described from west to east along the Westerschelde and at Tollesbury and Schleswig Holstein at the end. Fig. 8.1 gives a simple overview of all measured tussock shapes and sites at the Westerschelde and at Tollesbury.

Tussock shape at different sites

		shape						
		Total Count	depression Count	dome Count	cliffed Count	mushroom Count	terrace Count	topography Count
Site	Baarland (BAA)		1	1	0	0	0	3
	Hoofdplaat (HOO)		2	1	0	0	5	0
	Hooge Springer (HoS)		0	7	1	1	1	1
	Paulinapolder (PAU)		1	3	0	1	1	0
	Plaat van Walsoorden (PvW)		1	5	2	0	0	2
	Plaat van Baarland (PvB)		0	6	1	0	0	3
	Zuidgors (ZUI)		6	1	0	0	3	1
	Tollesbury (TOL)		0	22	0	0	0	0
	Total	83	11	46	4	2	10	10

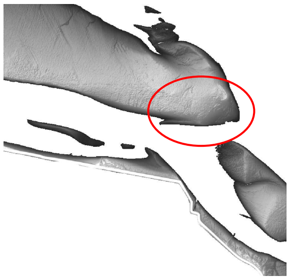
Fig. 8.1 Overview of tussock shapes and sites

The grain size of the surface sediment is representing the current velocities of the prevailing flow. The higher the current velocities, the bigger the deposited grain sizes. (LE ROUX, 2005) Fig. 8.2 gives an overview of the median grain sizes (D50) of the reference samples of each tussock at all field sites.
The samples of Hoodplaat (Hoo) and Baarland (Baa) are all ranging within the silt fraction (2-63 µm) whereas Paulinapolder (Pau) , Plaat van Baarland (PvB) and Zuidgors (Zui) have tussock at the silt and the sand (>63 µm) fraction.
Hooge Springer (HoS), with the highest maximum, and Plaat van Walsoorden (PvW) have coarser sediment in the sand fraction but the maximum of PvB is still higher than the maximum of PvW. Tollesbury (Tol) is the site with the finest sediments because of its sheltered location. The monitoring report of the restoration site gives further details about the Sediment properties at Tollesbury (WATTS in DEFRA 2008).

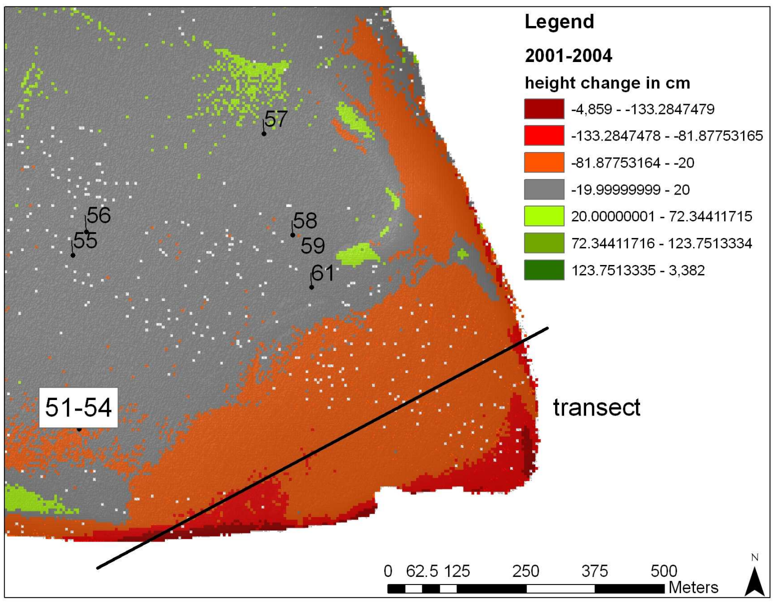
site	mean D50 (µm)	N	std. deviation (µm)	minimum D50 (µm)	maximum D50 (µm)
Baa	46.301	5.000	5.637	36.520	50.387
HoS	126.171	11.000	37.804	76.120	215.310
Hoo	48.054	8.000	4.156	40.370	55.160
Pau	50.722	6.000	8.392	45.503	66.990
PvB	85.788	10.000	22.111	55.820	124.593
PvW	98.629	10.000	4.529	92.777	105.960
Tol	23.794	22.000	4.700	17.193	32.467
Zui	64.130	11.000	12.891	39.747	80.033
Total	64.834	83.000	38.417	17.193	215.310

Fig. 8.2 Median grain size (D50) site comparison

a) Hooge Springer



The east side of Hooge Plaaten is called Hooge Springer, as it was a separate tidal flat before. The site is sandy, very inhomogenous and therfore considerd to be highly dynamic in some places but a trend in the physical state of the flat is visible.



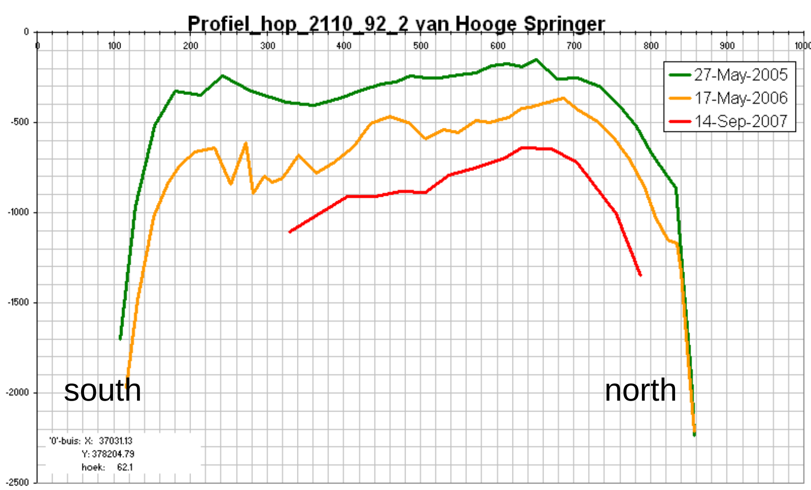


Fig. 8.3 Physical state of Hooge Springer, showing the DEM height change analysis and the transect

Hooge Springer is eroding from east to west, while there is still accretion on top of the flat. Especially tussocks 51-54 are situated in an eroding environment. East of these tussocks a lot of mushroom shaped and cliffed tussocks were observed in the field.

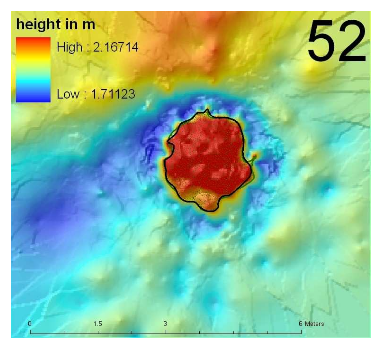


Fig. 8.4 Tussock 52

Therefore it is assumed, that these tussocks are characteristic for erosive environments.

The transect of RWS, which is indicated in the DEM, shows that this erosion has been continuing until 09/07. Tussocks no 57- 60 are much flatter because they are positioned higher up the tidal flat and shelterd by a ridge of sand and shells (Fig. 8.5).

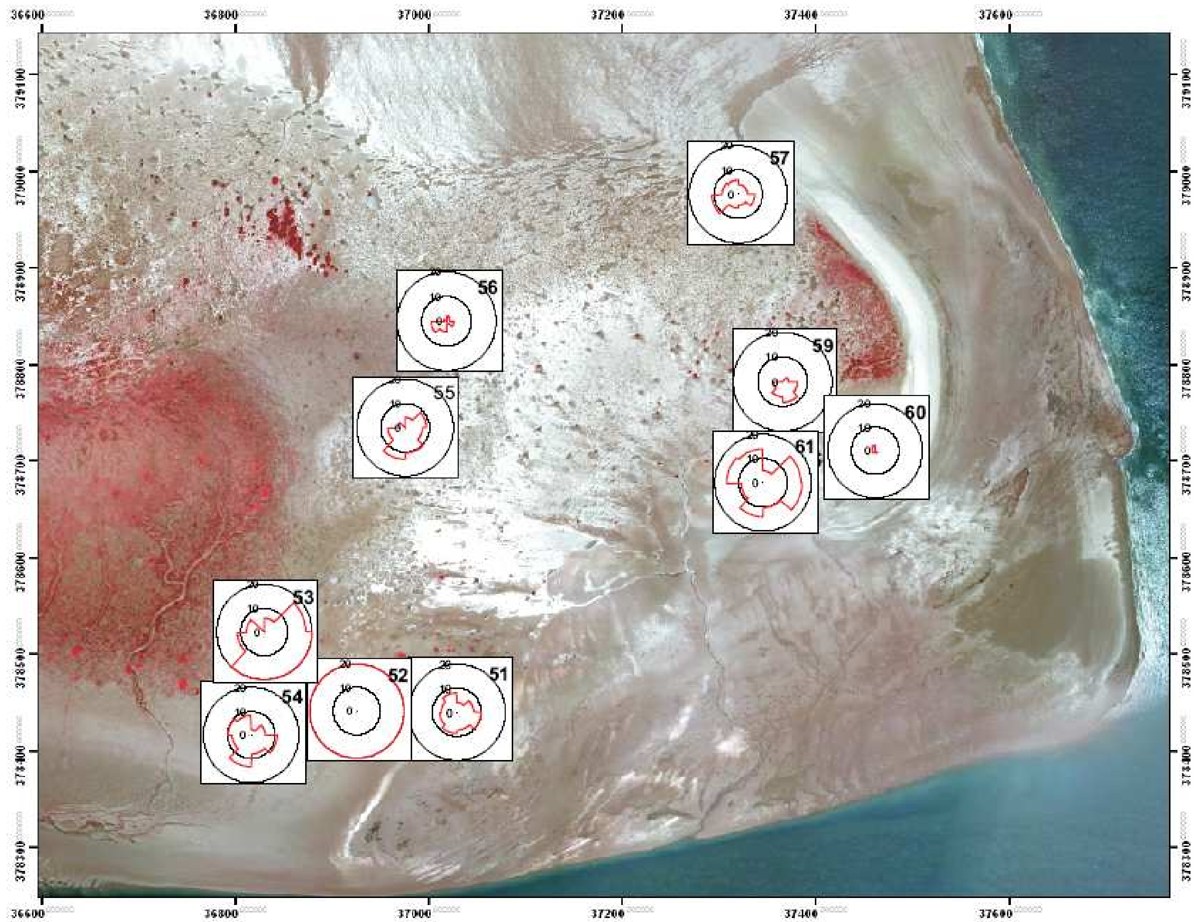
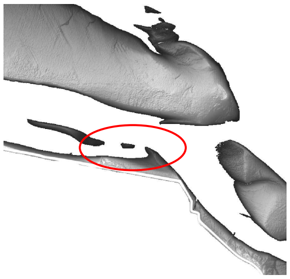


Fig. 8.5 Slope diagrams (chapter 7.1.2) of all elevated tussocks at Hooge Springer 2008. Slopes reaching 30° indicate a cliff.

b) Hoofdplaat



Hoofdplaat is a salt marsh forming due to a groyne at the west side of the marsh. The salt marsh is expanding eastwards in form of merging Spartina anglica tussocks directly in front of a dyke located in the south.

The site has sediment in the upper silt fraction, a lot of pools and channels forming the micro relief.

These tussocks showed very regular patterns in their slope.

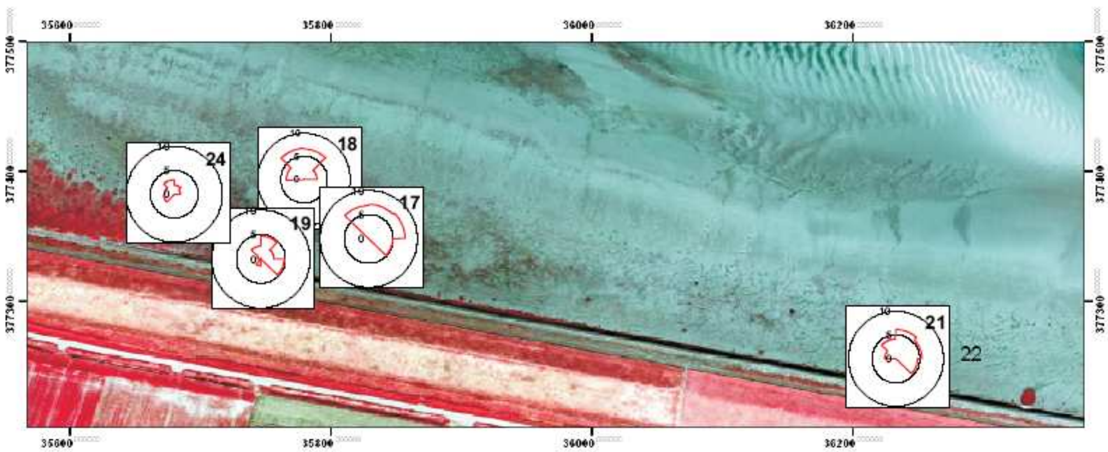


Fig. 8.6 Slope slices of all elevated tussocks at Hoofdplaat

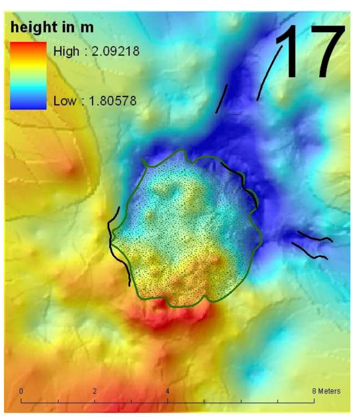
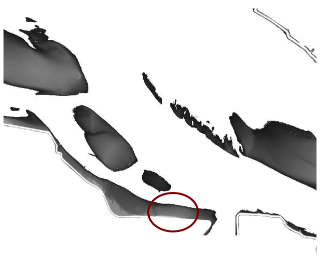


Fig. 8.7 Tussock 17 **Fig. 8.8 Hoofdplaat tussocks, NW view**

All tussocks of a certain size show a terrace shape in north-east direction with a Y shaped gully, the wake zone of each tussock is elevated. All small tussocks at Hoofdplaat are situated in a depression. For Hoofdplaat no sediment transects of RWS are available but the calculation of the DEM difference showed very little erosion at the whole site.

The north-east orientation could be explained by the main flow direction of the currents, also wave impact is possible because the fetch is biggest in this direction but easterly winds are very seldom. Hoofdplaat gives clear evidence, that Spartina tussocks influence their topography in a regular pattern depending on existing processes.

c) Paulinapolder



At Paulinapolder, at the south bank of the estuary near Terneuzen, only tussocks at the east part of the marsh were measured.

No regular pattern for those tussocks was found because different pathways of flow caused an inhomogeneous topography. Tussock 25 for example is forming a depression although it is a rather big tussock which should be able to trap sediment. Tussocks 27 and 28 show lateral erosion on both sides which let the tussock appear as elevated. As seen on the aerial photograph (Fig. 8.9) different channels are visible which seem to influence the main flow direction and hence the tussock topography. Both the DEM difference and the RWS transects do not show a certain trend of overall erosion or sedimentation.

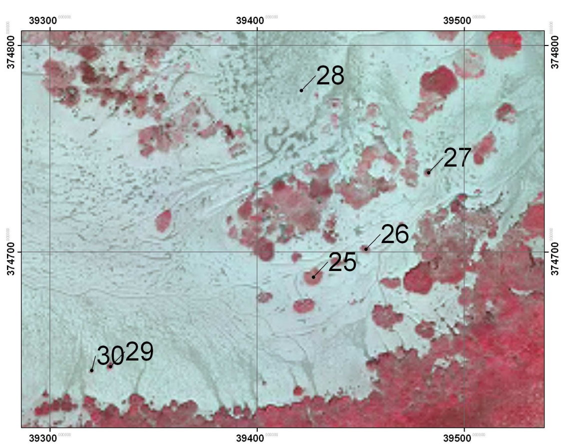


Fig. 8.9 Overview of Paulinapolder east 2008

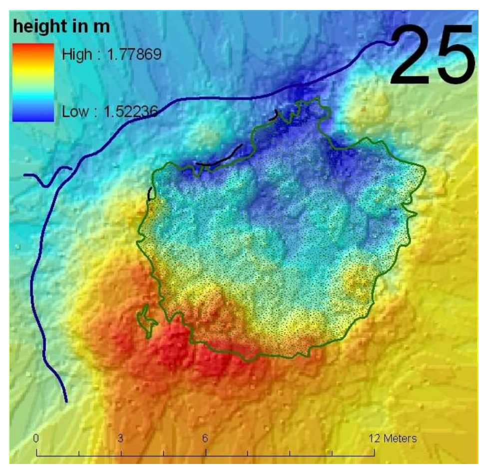
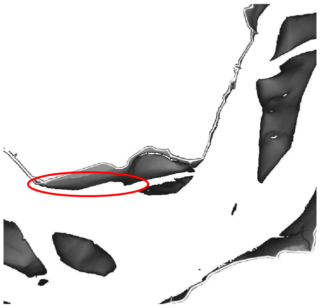


Fig. 8.10 Tussock 25

All tussocks are located in a sandy area despite tussock 29 and 30 which are situated closer to the dyke at a rather muddy spot.

A speciality of the tussocks at Hoofdplaat is that within the vegetation a lot of shells are deposited which can have an effect on tussock topography.

d) Zuidgors



Zuidgors is a marsh with a retreating cliff located on the north bank of the Westerschelde (VAN DER WAL et al. 2007)
The whole flat in front of the cliff is accreting as shown in the sediment transects of RWS (Fig. 8.12).
The transect 2270 shows that the area near tussock 15 and 16 is stable and not as fast accreting as near the tussocks 5 to 13 at the west side (not all tussocks shown in Fig. 8.11)
Whereas the sediment of tussock 13, 15 and 16 is consisting of more than 50% of silt, tussocks 5-12 have sandy sediment. They are all located several meters away from the cliff on the bare flat. They are exactly located on the line where the salt marsh cliff was situated in 1982 which makes the situation very unique.

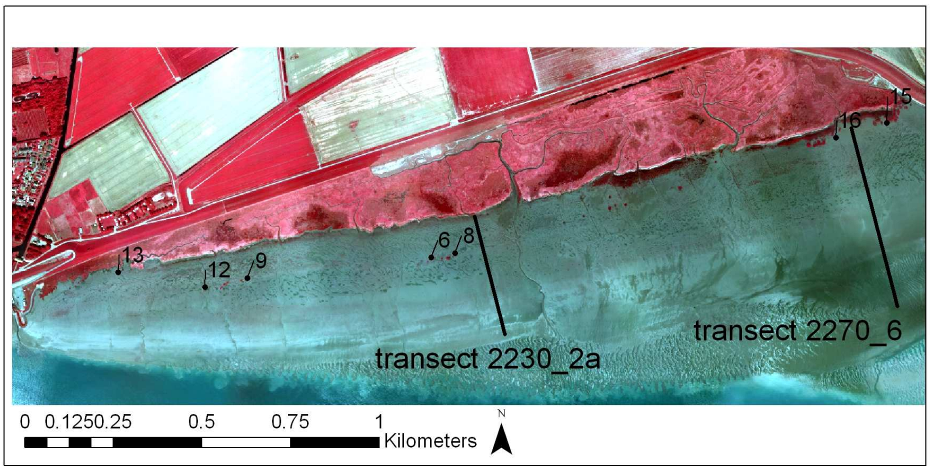


Fig. 8.11 Overview Zuidgors

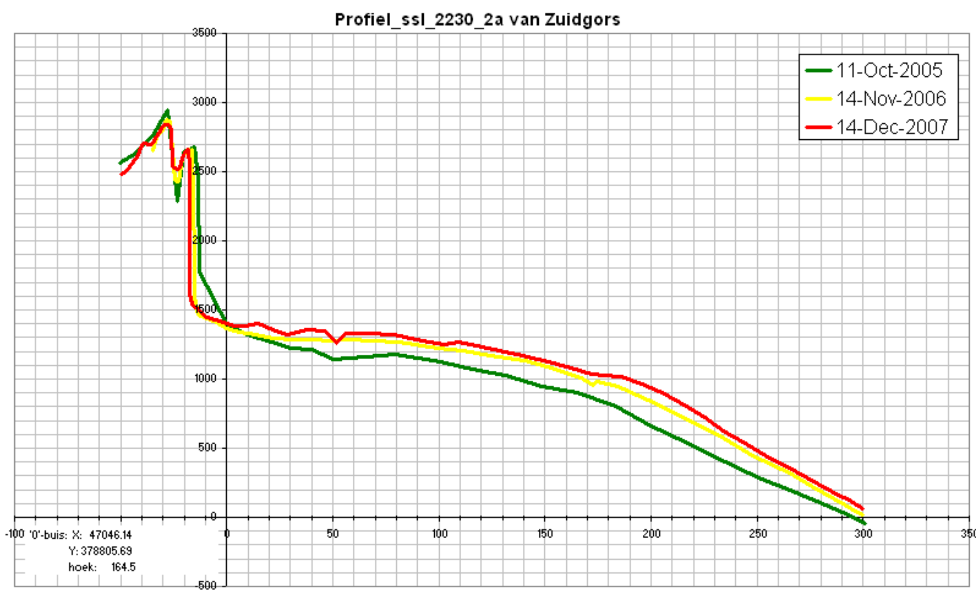


Fig. 8.12 RWS transect Zuidgors between 2005 and 2007 showing constant accretion of the tidal flat in front of the salt marsh cliff

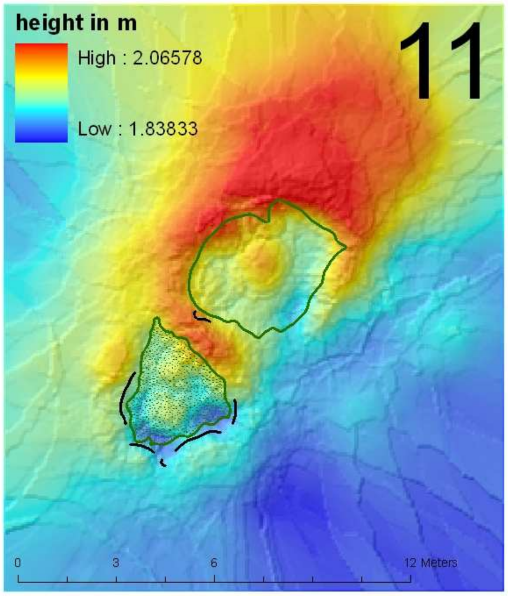


Fig. 8.13 Tussocks 11 (left) and 12

Tussocks 5 to 12 are situated at an exposed but accreting site. This explains why most of the tussocks form depressions but have an elevated wake zone. The currents are so fast that turbulences hinder the available sediment to settle within the vegetation (chapter 4.4.3), but once it leaves the vegetation patch particles can settle in the wake zone of the tussocks.

At these tussocks scouring around the stems within the vegetation was found which points to sediment movement and turbulence in the patch. Tussocks 15 and 16 instead have a terrace shape comparable to those tussocks at Hoofdplaat which is interesting because both sides are in a comparable situation concerning sediment composition and physical state.

e) Baarland and Plaat van Baarland

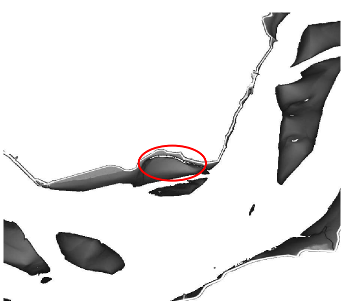


Fig. 8.14 Overview of Baarland

Baarland has very fine sediment and is a stable salt marsh located east of Zuidgors and dissected from the Plaat van Baarland with a steep but small channel. The north side of Plaat van Baarland is muddy whereas the exposed south side has sandy sediment.

As seen in Fig. 8.16 the south side was eroding between 2001 and 2004 and the RWS transect data is confirming that this process has been continuing at least until 2006. Tussock 31-33 and 38-40 (not all shown on the map) are all located on the south side close to the indicated erosion of the tidal flat and they are all elevated. A lot of tussocks in the vicinity have cliffs (like tussock 38, Fig. 8.15) or showed erosion in form of bare roots or dead Spartina stems. Tussock 40 and tussock 39 directly next to it have parallel gullies on the west and east side of the tussock which show that bidirectional flow is dominating on the crest of the tidal flat.

All tussocks at the south side of Plaat van Baarland are elevated whereas those at the north side (34-37) stay flat, also the tussocks at the salt marsh of Baarland (1-4) are following topography and are not elevated. Only tussock 14 which is the biggest measured tussock with about 120 m² showed a dome shape.
Dewatering channels shape the microrelief of the salt marsh.

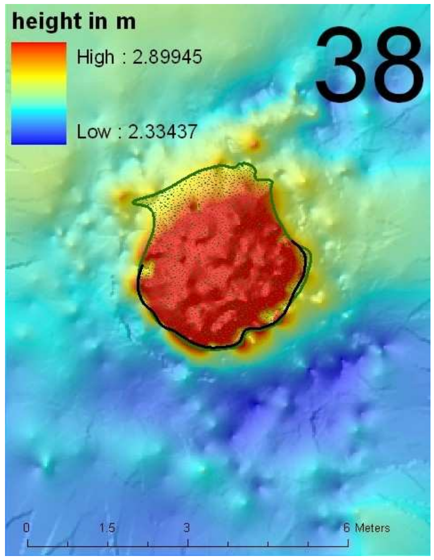


Fig. 8.15 Tussock 38 with cliff

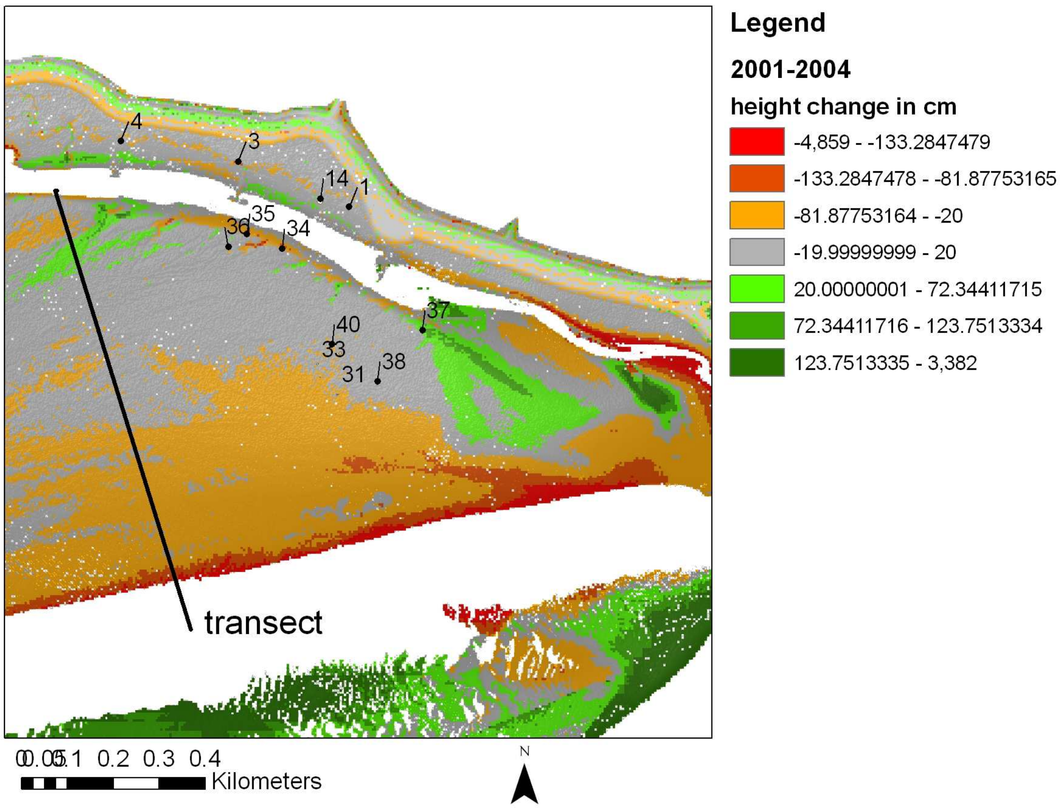


Fig. 8.16 Physical state: DEM height change calculaton of Baarland and Plaat van Baarland (tussocks 31-40)

f) Plaat van Walsoorden

The eastern part of Plaat van Walsoorden is characterized by a steep retreating edge in the north (Fig. 8.17) The height change between 2001-2004 reveals the existence of mega- ripple like structures where sedimentation and erosion alternate.

Although tussocks 48 and 47 are located in an accreting area (2001-2004) these tussocks and their neighbours showed clear erosion in the field. It is assumed that this mega-ripple structure has shifted and therefore the height change data can not be used for further analysis. The tussocks showed a big variety, dome shaped and flat tussocks occurred next to cliffed tussocks (see chapter 8.2).

Striking is that only two out of ten tussocks have already been there in 2004, this might be explained by the progressing mega- ripples (see addendum).

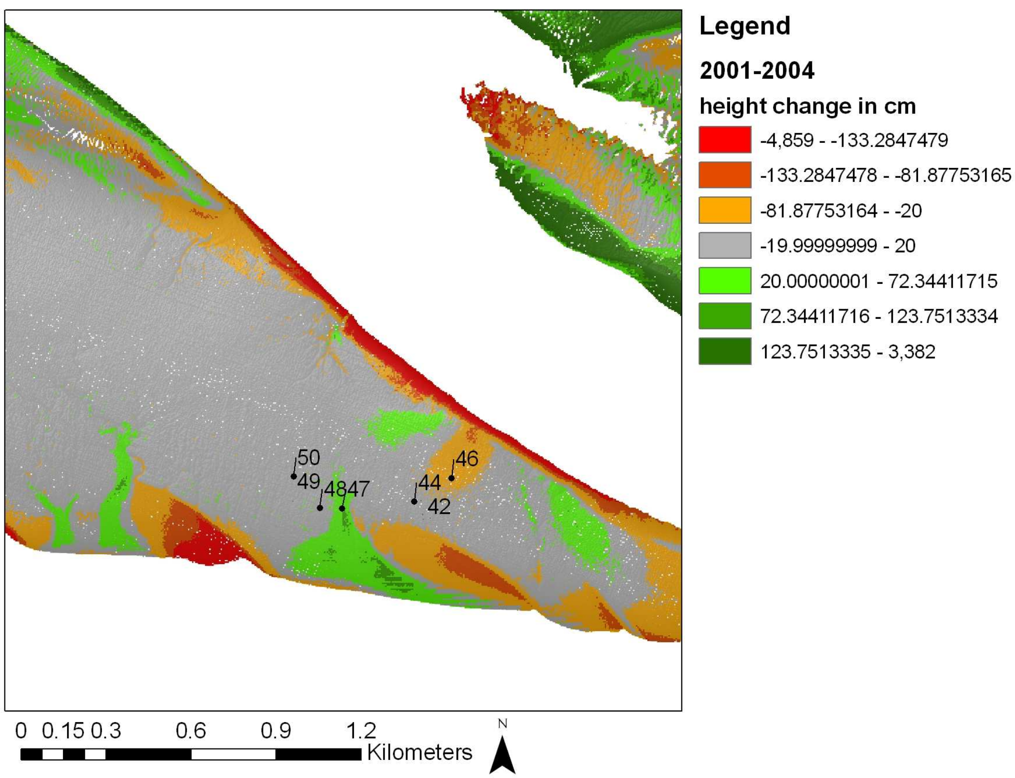


Fig. 8.17 Physical state: DEM height change calculation of Plaat van Walsoorden (east) showing alternating erosion sedimentation structure at the south side

g) Tollesbury (UK)

The tussocks at Tollesbury are dome shaped without exception (Fig. 8.20).
Fig. 8.19 shows that tussocks T1-T10 are located at the west side of the marsh and tussocks T11-T22 in the middle.
The analysis of the sediment transects show different sedimentation rates for all tussocks ranging between 0.4 and 2.26 cm/ year (8.18).
Surface elevation was measured every year at the same transects within the monitoring programme so that detailed sedimentation data is available (GARBUTT in DEFRA 2008).

tussocks	cm/year
Tol1-8	0.425
Tol9,10	0.985
Tol11-15	1.21
Tol16	2.26
Tol17-20	1.1
Tol21	0.86
Tol22	1.21

Fig. 8.18 Sedimentation rates [2003-2007] at Tollesbury near the measured tussocks (DEFRA 2008)

Also the strength and stability of the sediment has been monitored. In the pioneer zone shear strength between 5 and 70 kPa was found whereas shear strength and sediment stability increased with colonisation of Spartina anglica tussocks from 0.6 kPa to 2.5 kPa. Both Spartina and Salicornia prefer to colonise creek margins as the shear strength is up to 18kPa at these ridges. For all measurements a CSM (Cohesive Shear Stress Meter) was used (WATTS in DEFRA 2008). Aerial photographs of summer 2005 are provided by the Environment Agency and used to determine long term growth rates of the tussocks.

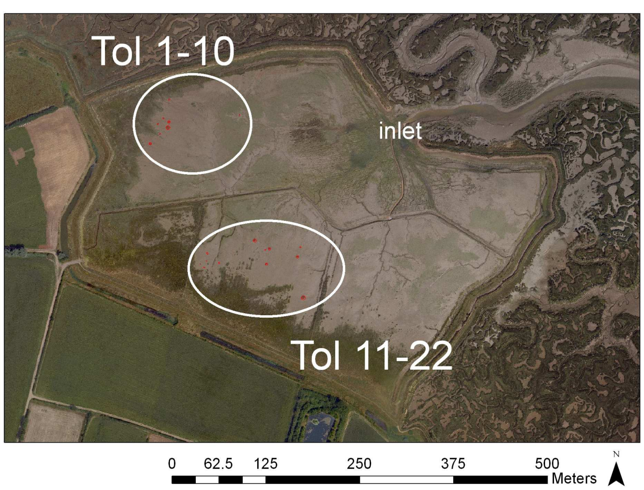


Fig. 8.19 Overwiev of Tollesbury (2005) (Source: Environment Agency)

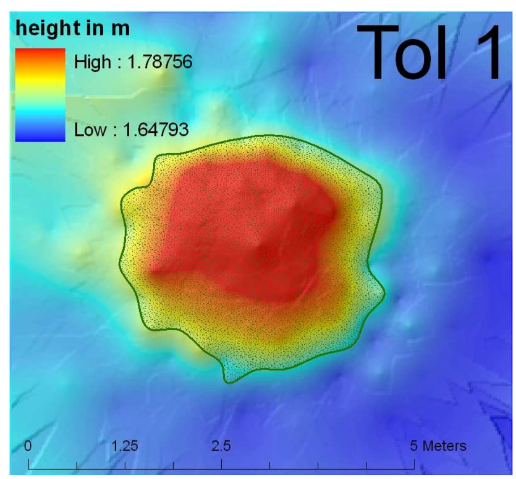


Fig. 8.20 Tussock Tollesbury (Tol) 1

h) Tuemlauer Bucht

At the Tuemlauer Bucht sedimentation fields are not maintained anymore and the dewatering causes channel erosion which is starting to leave its old pathways. On the aerial photograph (Fig. 8.21) the tussock colonisation seems to follow the old structures but is interrupted where channels are forming. The tussocks are all dome shaped at this site and do not have gully formation because it is a very muddy and sheltered site. Due to this low energy environment the effect of dewatering channels was very obvious in the field (see chapter 8.2 Small scale differences in tussock topography).

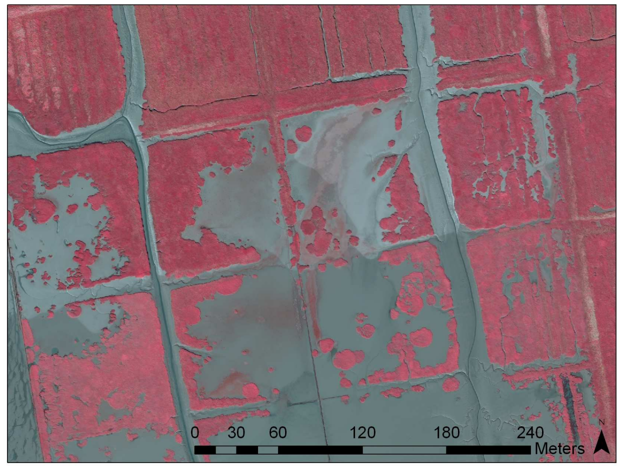


Fig. 8.21 Aeriel photo of Tuemlauer Bucht (Source: Nationalparkverwaltung)

i) Trischen Damm

Although the tussocks at the north side of the Trischen Damm are situated in still existing sedimentation field structures they are terrace shaped and cause scouring especially in the front of the tussocks (Fig. 8.22) like tussocks at Hoofdplaat. The in- and outlets of the sedimentation fields are also causing erosion which hints to high current velocities. The gullies of adjacent tussocks are merging to channels which support the theory of channel formation due to vegetation presence.

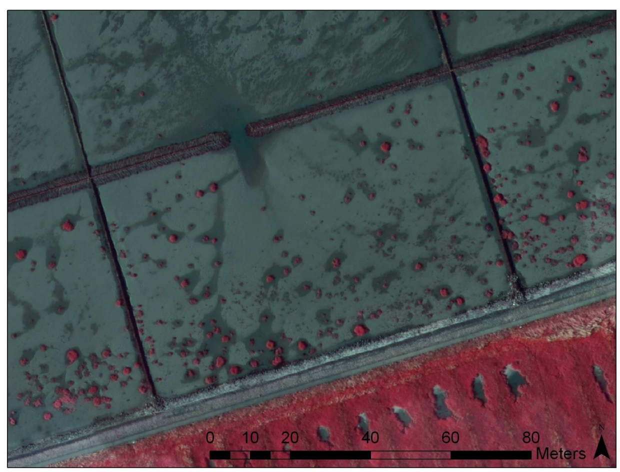


Fig. 8.22 Aeriel photo of sedimentation field at the North side of the Trischen Damm (Source: Nationalparkverwaltung)

However in this case channel formation does not occur due to flow enhancement between patches (Temmerman et al. 2007).

8.2 Small scale differences in tussock topography

Next to those differences which are discovered between sites or at different locations at a salt marsh or tidal flat small scale differences were discovered in the field.
Especially the dewatering of a salt marsh which causes channel erosion can influence the tussock topography or even destroy whole tussocks. Channel erosion is most likely at muddy sites where low permeabilities lead to surface runoff as the water table lowers (LE HIR et al. 2000).
Fig. 8.23 shows tussocks at the Tuemlauer Bucht salt marsh in Germany. The tussock has a high slope on the side which is facing the channel due to erosion. The height difference between tussock dome and mudflat on the left hand side is much smaller.
This shows that the height difference due to enhanced sedimentation (left) is smaller than the height difference caused by sediment dynamics of the mudflat (right).

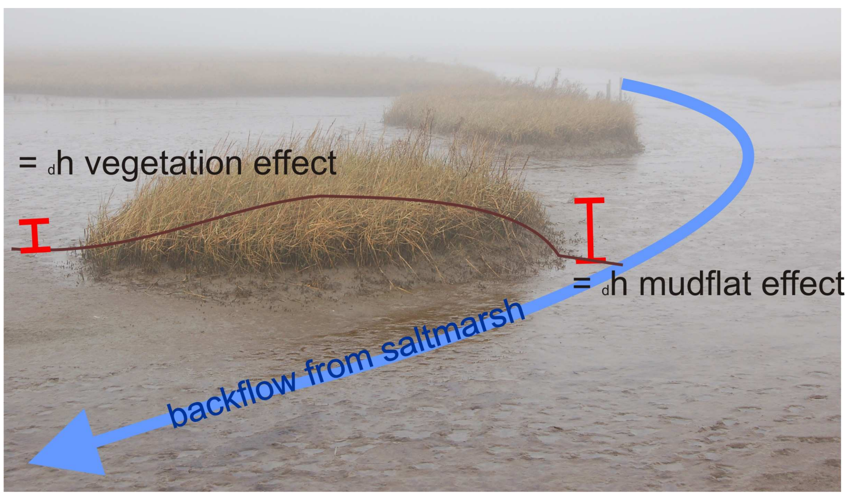


Fig. 8.23 Tussocks at Tuemlauer Bucht, showing increased steepness of tussock edge due to channel formation on tidal flat compared to steepness without channel on the left side

Also the analysis of aerial photographs of Plaat van Walsoorden for example showed that adjacent tussocks developed different, while tussock 48 was growing, all tussocks around it where eroding between 2004 and 2008 (see addendum). A closer look reveals, that channel formation is the reason that tussocks disappear selectively without general patterns. This causes a problem in predicting tussock development because routes of channels can change from year to year and are not clearly predictable.

8.3 Tussock topography synthesis

Concerning the theory that dome shaped tussocks develop due to reduced hydrodynamics and hence enhanced sedimentation within the vegetation it became already clear in the field, that this can not be the driving process for all dome shaped tussocks. Fig. 8.25 shows a clearly elevated tussock with nearly dead Spartina anglica stems. It is obvious that this tussock is not able to trap enough sediment to form a dome shape. The site comparisons of the sandy tidal flats display that tussocks with the highest dome elevations compared to the tidal flat occur in erosive environments (Fig. 8.24, topo2). If the surrounding sediment level drops rapidly the roots of the tussock get undercut and mushroom shaped tussocks form (topo3). These pillar like structures cause scouring around the tussock that can be several cm deep. Sediment trapping can still play a role in forming elevated tussocks also on exposed tidal flats but the sediment binding of the roots and the resistance to erosion form dome shaped tussocks that are much higher elevated. In contrast Zuidgors is rapidly accreting in front of the cliff but the tussocks are situated in a depression whereas the wake zone of the tussocks is elevated. Because the tussock situation is exposed high current velocities are expected. Stem scouring points to high turbulence within the vegetation which hinders the sediment from settling, once the suspended sediment leaves the vegetation turbulence breaks down and sediment settles do to reduced velocities. Also at Hoofdplaat enhanced turbulence in the front of the tussock could cause the terrace shape and the elevated wake zone. It is likely that the turbulence in the front proceeds through the whole vegetation if current velocities increase. Tussocks in a stable and sheltered environment like Baarland remain flat. Only tussocks in accreting and sheltered environments like Tollesbury behave according to the theory as sediment traps and form dome shapes.

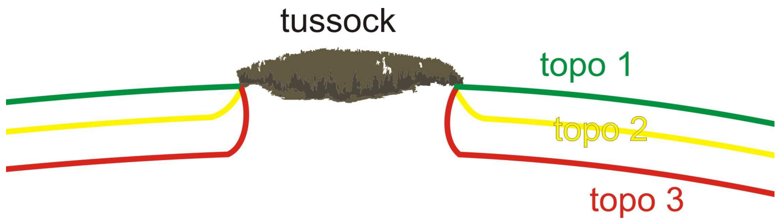


Fig. 8.24 Tussock in an erosive environment. Starting from a slightly elevated tussock (1) to a dome shaped tussock (2) ending with a mushroom shape (3).

Fig. 8.25 Dome shaped tussock at Plaat van Baarland with nearly dead vegetation whereas other tussocks on the same tidal flat were still in good shape.

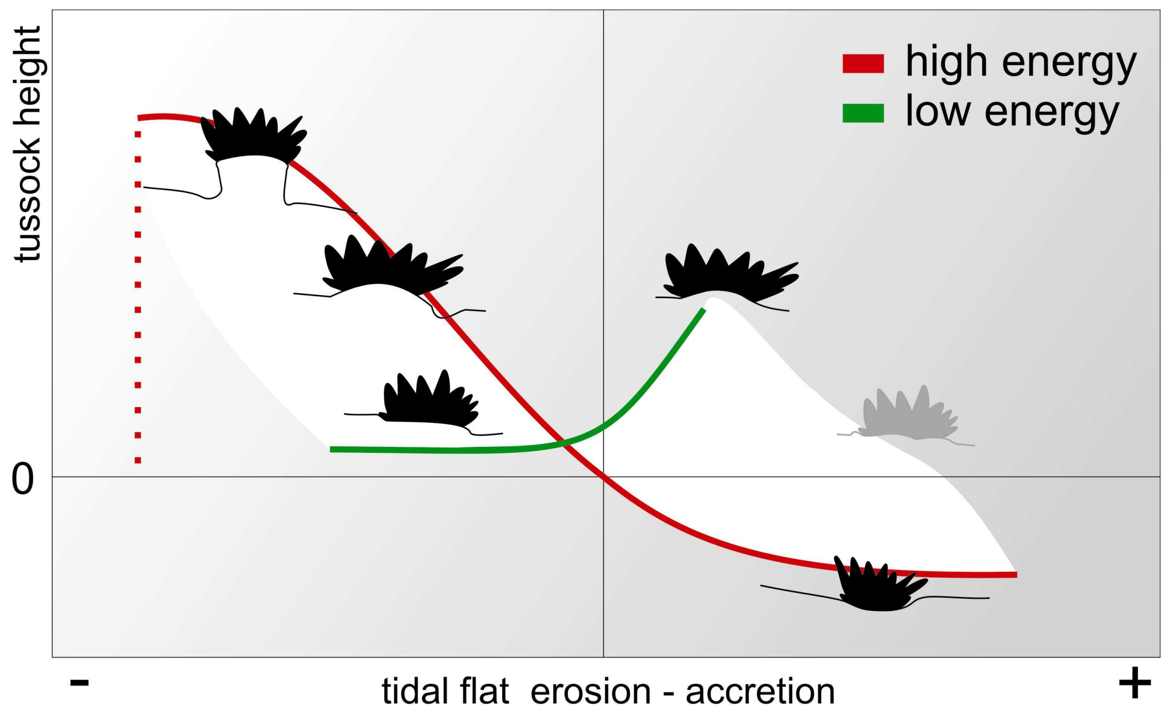


Fig. 8.26 Tussock topography synthesis. High energy tussocks are representing exposed sandy sites whereas the low energy curve is representing sheltered and rather muddy sites. The white area indicates the intermediate states.

Fig. 8.26 shows the reported findings in a conceptual synthesis diagram. The height difference of tussock to tidal flat is a proxy for tussock shape. The tidal flat sediment dynamcis are expressed in rates of tidal flat accretion or erosion.

Exposure and physical state of the tidal flat are the main factors influencing tussock topography. This scheme tries to simplify a complex system with different processes at the same time. Whereas mushroom shaped and dome shaped tussocks (high energy environment) occur due to sediment binding of roots dome shaped tussocks (low energy environment) occur due to enhanced sedimentation and tussocks in a depression (high energy) likely have their topography due to flow turbulence in the vegetation. Moreover this system is depending on the tussock size so that this concept is only valid for tussocks above a certain size, but this threshold also differs between processes. Very small tussocks form most likely a depression due to turbulence. At erosive sites however also mushroom shaped tussocks with a diameter of about 30cm and smaller were found. A special case which has not been found within this study is extreme sedimentation within a sheltered site. This is very unlikely to happen but measurements showed that sedimentation rates in the patch did not differ from sedimentation on the mudflat at extreme high sedimentation rates. This would theoretically result in flat tussocks (WARD et al. 2003). Once the mushroom shaped tussocks get eroded away the height difference drops to zero and the tussock is gone (dotted line).

8.4 Analysis of topography data

The statistical analysis of the existing data is based on the tussock topography synthesis (Fig. 8.26).

Because tussock topography is size depending all analysis are describing tussocks between 2 and 30m².

By using the DEM 2001-2004 data for the Westerschelde tussocks and the sedimentation data for Tollesbury tussocks as x-axis and the height difference of the tussock to the calculated reference plane (Chapter 7.1.2) as y-axis, the cloud of points should lie between this maximum response curves of the synthesis diagram because all tussocks are included. Because the DEM data of Plaat van Walsoorden is not representing the recent development as described in chapter 8.1.f) this data is excluded.

The trend lines in Fig. 8.27 show that all tussocks (between 2 and 30m²) follow the expected trend of the synthesis.

The picture is most clear for tussocks in a depression and for mushroom shaped and cliffed tussocks. Tussocks which follow the topography are spread and have to be analysed carefully because the topography of the tidal flat or salt marsh is causing the height differences and not a regular pattern. Considering that the elevation change data for the Westerschelde is 4 years old a much better relationship can be achieved as soon as the new elevation model of the Westerschelde becomes available. To distinguish between high and low energy tussocks the median grain size of the reference sample is used. Already the categorisation of sand or silt (50% silt threshold) shows that the conceptual synthesis is true. By putting the threshold up to 60% silt content to determine high and low energy tussocks the oppositional behaviour is described best. The height difference of the <60% silt tussocks is significantly correlating with the elevation change (Person correlation: 0.45, 0.01 level) Variance is too high for the >60% silt regression to reach a significance level, but these tussocks have no extreme height differences as expected. It has to be considered that the elevation change data for the Westerschelde is not recent enough to get the perfect relation and small elevation changes can not be measured with the LIDAR, but it is satisfying for extreme situations like Zui and HoS (Fig. 8.32, Pearson correlation 0.889, 0.01 level).

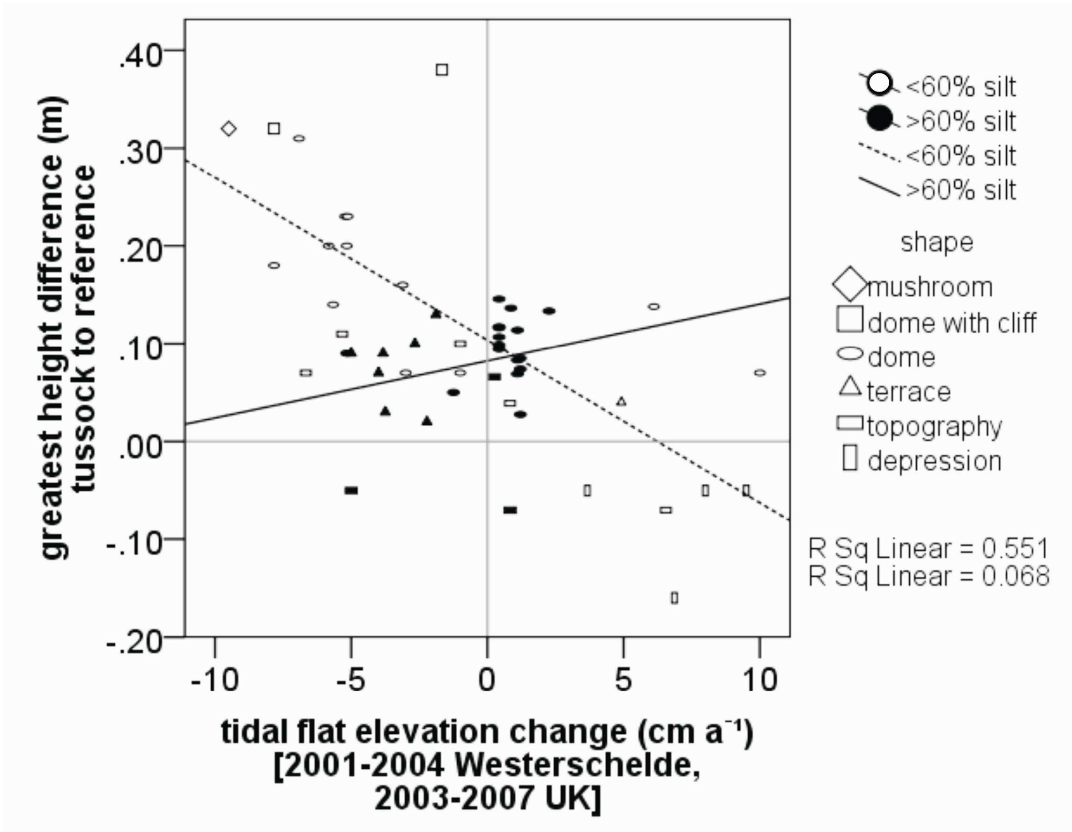


Fig. 8.27 The height difference of tussock to reference is a result of the elevation change of the tidal flat as shown in the tussock synthesis. The relation is most clear for tussocks at sandy (high energy) sites. Tussocks at silty sites have no clear relation but do not show big height differences. Linear trendlines are indicated. (N=50) all tussocks between 2 and 30m² (without PvW)

The precise analysis of the dome volume reveals the already mentioned differences between elevated tussocks in contrasting environments.

The dome volume of all dome shaped tussocks at the three tidal flats (Hos, PvB, PvW) and the tussocks of Tollesbury were calculated in comparison to a reference plane of all measured points outside the tussock (Fig. 8.28). Tussocks at Tollesbury are flatter than those of the Westerschelde because of the already described different processes.

The majority of the dome shaped tussocks at those 3 tidal flats are situated in an erosive environment. A regression line through the cliffed and mushroom shaped tussocks would even show a greater volume-size relationship. It is expected that there is a third threshold line between both regression lines that indicates which maximum volume the tussocks in an accreting environment could reach. This line would represent the maximum volume/size which can be reached due to sediment trapping. Domes exceeding this imaginary line, with higher volumes per area, can only be explained with erosion around the tussock. However some of the tidal flat tussocks of the

Westerschelde seem to follow the Tollesbury tussocks. The outliers might be situated in an accretional environment but the data is not able to proof this.

Because all dome shaped tussocks of the three tidal flats were chosen the variance within the sample is high. The elevation change data for HoS and PvB shows that 12 out of 13 dome shaped tussocks are situated in an erosive environment, the elevation data for PvW is not valid but erosion was observed in the field.

WARD et al. 2003 described that there is no difference in sedimentation within tussocks and next to tussocks at extreme sedimentation rates (about 10cm/year) which would result in a flat regression line on this graph for extreme accretional and sheltered environments.

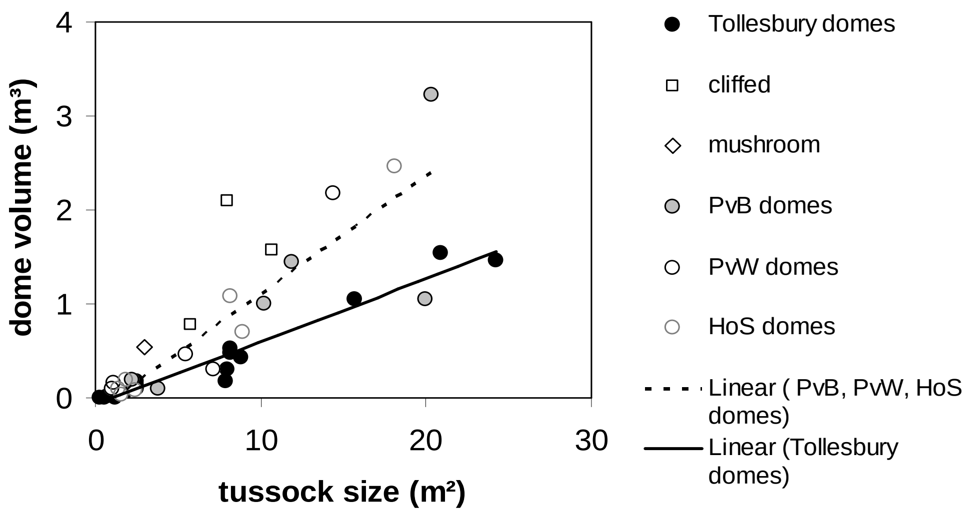


Fig. 8.28 Dome volume and size of tussocks. Dome shaped tussocks at Tol are flatter than domes at the tidal flats of the Westerschelde.
Linear Tollesbury: 0.0667x-0.0681 [R^2=0.956]
Linear PvB, PvW, HoS domes: 0.1254x-0.1496 [R^2= 0.7885]

A closer look at the Tollesbury tussocks also revealed the stagnation of dome height with increasing size (Fig. 8.29) which SANCHEZ et al. 2001 found as well (see chapter 4.4.2). Although the volume is still increasing because the area of the tussock is growing, the dome height of tussocks with elevation due to enhanced sedimentation starts to stagnate at a certain size. SANCHEZ et al. 2001 found that this maximum height for Spartina maritima domes is 25 cm for tussocks with 25m diameter. The biggest tussock in Tollesbury has 5m diameter and is about 14 cm elevated whereas a 2.5m diameter tussock is about 8-10 cm elevated which fits the data of SANCHEZ et al. 2001 nicely (see Fig. 4.3, Population B and C).

For the tussocks at the Westerschelde this relation was not found because they develop due to a different process.

So the question raises how to distinguish between the two different domes? To give them two different names, dome shapes in an accreting environment are from now on called: **"balanced domes"** because they reach their elevation only due to their own sedimentation capability and dome shapes in an eroding environment are called: **"unbalanced domes"** because erosion around the tussocks is causing an exaggerated elevation of the dome. Whereas most of the publication about dome shape are referring to balanced tussocks (SANCHEZ et al. 2001, CASTELLANOS et al. 1994, WARD et al. 2003) with a logarithmic relation between size and height this study suggests that tussocks above this relation (here defined with the regression of Tollesbury) are not balanced and therefore have no relation to size. Although differences in vegetation properties between both were not found but in the field the unbalanced tussocks seemed to have more broken stems and were less green. Lateral expansion data is missing for 58% percent of tussocks of the tidal flats and therefore for the long the term growth rates. It is likely that unbalanced tussocks grow slower or erode and balanced tussocks solely grow. The available data shows that unbalanced tussocks can grow and erode.

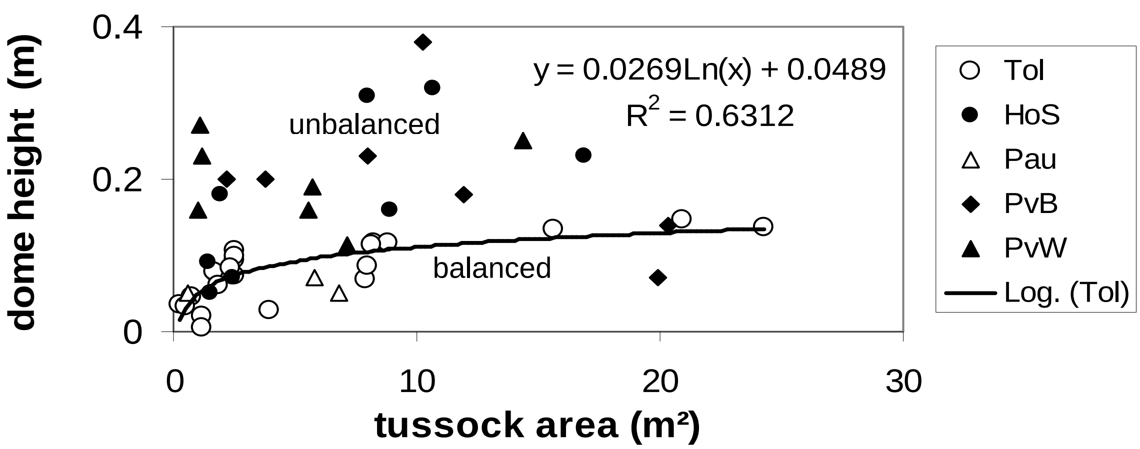


Fig. 8.29 Height of dome shaped and cliffed tussocks at shown locations (N = 47). Tussocks at Tollesbury (Tol) show a logarithmic size dependence due to the process of enhanced sedimentation whereas especially tussocks of the tidal flats (HoS, PvB, PvW) are situated above this line without showing any relation, most of them develop due to erosion around the tussock which is not related to tussock size.

8.5 Lateral growth of tussocks

As explained in 4.3 Spartina anglica has an expansion and die back cycle which is not yet fully understood.

For all tussocks at the Westerschelde no relation between lateral tussock expansion and elevation to hydrographic zero at the tidal flat or salt marsh was found and because of the differences between all the sites and the small scale effects this is not surprising.

But one relation was found to be significant for all tussocks at all sites, size dependence.

Whereas the radius of eroding tussocks shrinks in a constant rate between 0 and -10 cm per year, growing tussocks show a size dependent growth rate (Pearson correlation: 0.923, 0.01 level). The graph (Fig. 8.30) shows that tussocks which are bigger grow faster than smaller tussocks. Considered in a time scale this means, that the growth of tussocks is exponential as the growth rate increases with size from year to year. Only tussocks which were existent between 2004 and 2008 can be described because data is lacking for the others. (Tussock 14 is excluded because of its size (122m²) and because it merged with smaller tussocks in the past) Therefore this graph shows the long term development of rather consistent tussocks, short term developments in which tussocks can get eroded and grow back in no time, like on Plaat van Walsoorden, can not be analysed because yearly aerial pictures ore measurements are missing.

Size dependent growth rates for Tollesbury between 2005 and 2008 fit the growth rates of the Westerschelde tussocks. 8 out of 22 tussocks were already present in 2005 and hence could be analysed. Most of the new established tussocks were located near the Spartina meadow.

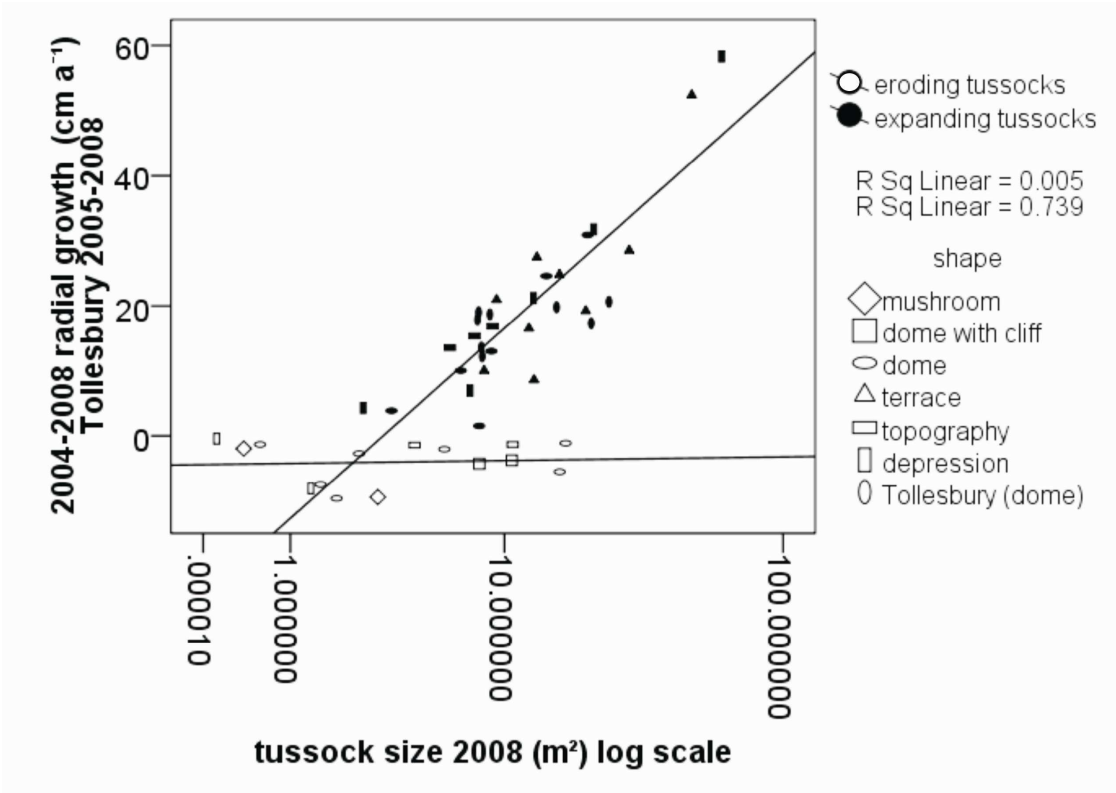
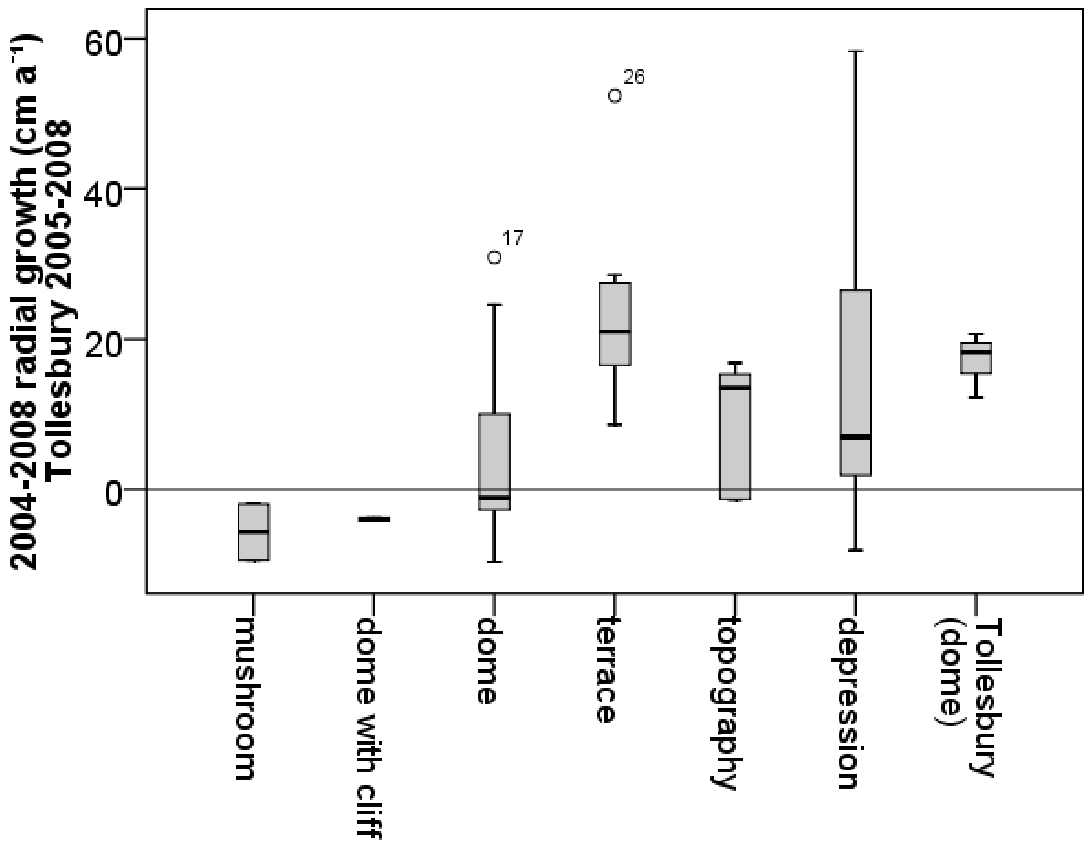


Fig. 8.30 Size dependent growth rate (Westerschelde: N=38, Tollesbury: N=8).
Function of all expanding tussocks: y = 15.536Ln(x) - 18.901
Erosion of tussocks is size independent.
Only tussocks which were already present in 2004 (2005) have been analysed.

It is described in the literature that larger Spartina spp. tussocks are situated at higher elevations than smaller tussocks (CASTELLANOS et al. 1994) and tussocks at higher elevations grow faster than tussocks closer to MHW. (VAN HULZEN et al. 2007)
Considering both findings this would result in a size dependent growth rate which was found in this study. It is likely that the theoretical growth rate is depending on both interdependent factors: elevation and size. However it is clear from the field and from the measurements, that the size of tussocks at the Westerschelde is not following an elevation gradient because smaller and bigger tussocks develop directly next to each other due to changing physical conditions.
It might be true for initial colonising situations of Spartina which is proceeding e.g. from the dyke to the channel, with older and bigger tussocks at higher elevations.
But also at Tollesbury this elevation-size relationship was not found because Spartina was colonising along channel ridges which have favourable sediment conditions. Because Spartina is not always colonising the mudflat parallel to the coastline and physical situations can change, describing lateral expansion of a tussock with its size is more precise to predict the future of a tussock although it might strongly depend on elevation and inundation.



Case Processing Summary

		Cases					
		Valid		Missing		Total	
	shape	N	Percent	N	Percent	N	Percent
2004-2008 radial growth in cm/year	mushroom	2	100.0%	0	.0%	2	100.0%
	dome with cliff	2	100.0%	0	.0%	2	100.0%
	dome	13	100.0%	0	.0%	13	100.0%
	terrace	9	100.0%	0	.0%	9	100.0%
	topography	5	100.0%	0	.0%	5	100.0%
	depression	7	100.0%	0	.0%	7	100.0%
	Tollesbury (dome)	8	100.0%	0	.0%	8	100.0%

Fig. 8.31 Shape and growth/erosion rates of all tussocks which were present in 2004 (Westerschelde), 2005 (Tollesbury).
Mushroom shaped and cliffed tussocks always erode.

Looking at the different shapes (Fig. 8.31), which are a result of the tidal flat physical state and exposure, a difference in growth rate is obvious.
Whereas all cliffed and mushroom shaped tussocks are eroding the statement for dome shaped tussocks is not clear as the mean expansion rate is zero.

If the sediment level around the dome shaped tussock drops too much tussocks get eroded and start to form a cliff if the process is continuing, whereas under favourable conditions dome shaped tussocks can expand.

Tussocks in a depression, flat tussocks and terrace shaped tussocks are growing on average.

By comparing the growth rate and height difference of tussock to flat of two extreme vertical accreting and eroding sites (Zuidgors, Hooge Springer) it becomes clear that tussocks start to erode when the sediment level change exceeds -5cm per year. Tussocks in this environment are elevated about 20cm.

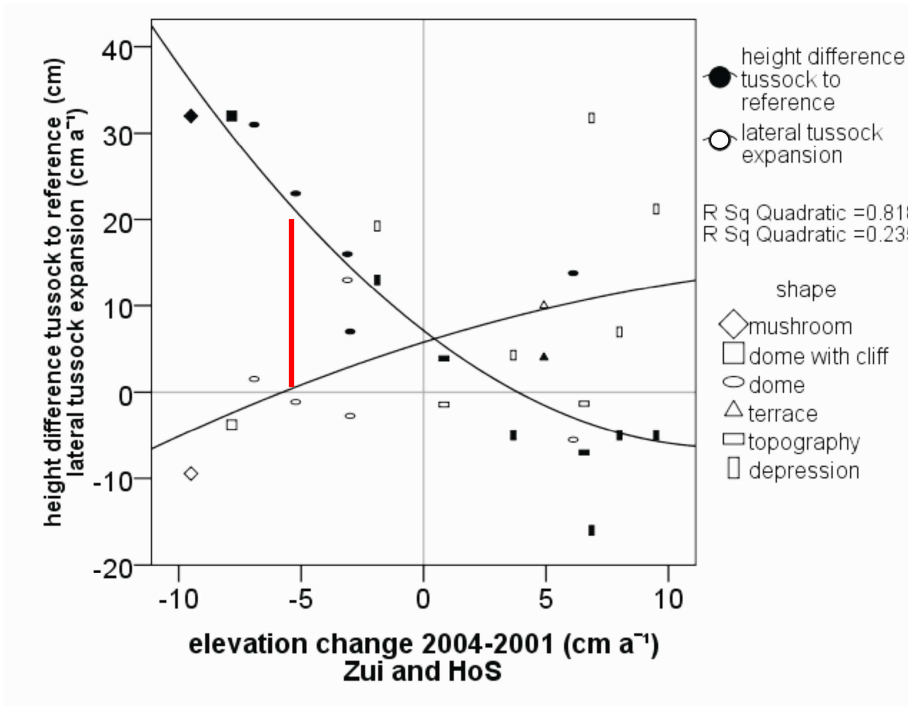


Fig. 8.32 Physical state to growth rate and height difference (tussocks at extreme accreting and extreme eroding sites of Zuidgors and Hooge Springer). Red bar indicates height threshold for erosion of tussocks. Function of height difference tussock to reference:
$y = 0.0887x2 - 2.1914x + 7.1276$

This hints to a roughly indicated threshold, tussocks which are higher than 20 cm compared to their surrounding start to erode laterally at exposed sites on the long run. This threshold however could be size dependent because the slopes for bigger tussocks are less steep than the slopes for smaller tussocks with the same height difference.

The growth rate for the accretional environment of Zuidgors seems not to be related to the physical state. The size dependence at Zuidgors is much higher.

But two tussocks at Zuidgors are also eroding, likely due to high current velocities or flow routing but data is missing in this respect and a precise prediction under which circumstances tussocks start to shrink can not be made with this dataset.

In general tussocks in accreting, stable or slightly eroding environments are expected to grow size dependently if no small scale effects influence the tussock.

As mentioned in the paper review chapter 4 it is suggested that dome shaped tussocks develop along with gully formation and that this scouring could hinder lateral expansion (VAN HULZEN et al. 2007, VAN WESENBEECK et al. 2008).

All 22 tussocks of Tollesbury have a clear dome shape but none of them has gully formation around it because of the sheltered conditions.

17 out of the 61 tussocks of the Westerschelde have a distinct gully but already 7 of them are terrace shaped tussocks of Hoofdplaat and Zudigors which are all growing (Fig. 8.33) It remains unclear if they grow in the direction of the wake or if they do not show any preferred direction because the geocorrection of the photos is not precise enough.

shape	count	percentage
terrace	7	70 %
mushroom	2	100 %
dome with cliff	3	75 %
dome	5	16.7 %

Fig. 8.33 Gully occurrence per tussock shape (only Westerschelde)

Only 5 dome shaped tussocks had a distinct gully formation whereas 2 of them showed lateral erosion, one showed expansion and 2 were not there in 2004.

Of all 15 eroding tussocks of the Westerschelde only 5 tussocks have a gully.

Therefore gully formation can indicate rough conditions but they are no general feature for dome shaped tussocks. It is possible that scouring can hinder lateral growth or even cause lateral erosion but it is no dominating process in tussock development dynamics.

Because the measurements are snapshots and the tussock expansion is a long term process (here 2004-2008) the results have to be handled with care and more frequent measurements are needed to analyse short term dynamics and preferred direction of lateral expansion.

Fig. 8.34 Gully formation at PvW

8.6 Differences in grain size and bulk density

It is assumed that finer grain sizes are found in the tussocks compared to its surrounding because of the reduced hydrodynamics within the vegetation (VAN HULZEN et al. 2007). The sediment analysis of all 83 tussocks did not prove this theory. At 53 tussocks the silt content was higher outside the tussock and at 30 tussocks the silt content is higher within the tussock. Also the tussocks of Tollesbury alone do not show a trend to higher silt contents or lower grain sizes within the vegetation. Bulk density is in general higher in coarse sediment because of grain structure, water content and porosity (SCHEFFER and SCHACHTSCHABEL 2002) and this relation was also found for the measured tussocks. Grain size and bulk density within the vegetation are stronger correlated (Pearson: 0.882, 0.01 level) than at the reference points (Pearson: 0.775, 0.01 level). Because the organic matter was not analysed it is not clear in which extend this is influencing the bulk density. The difference in bulk density between patch and reference (Fig. 8.35) is not clear, the variance is biggest for bulk densities of 1.5g/cm³.

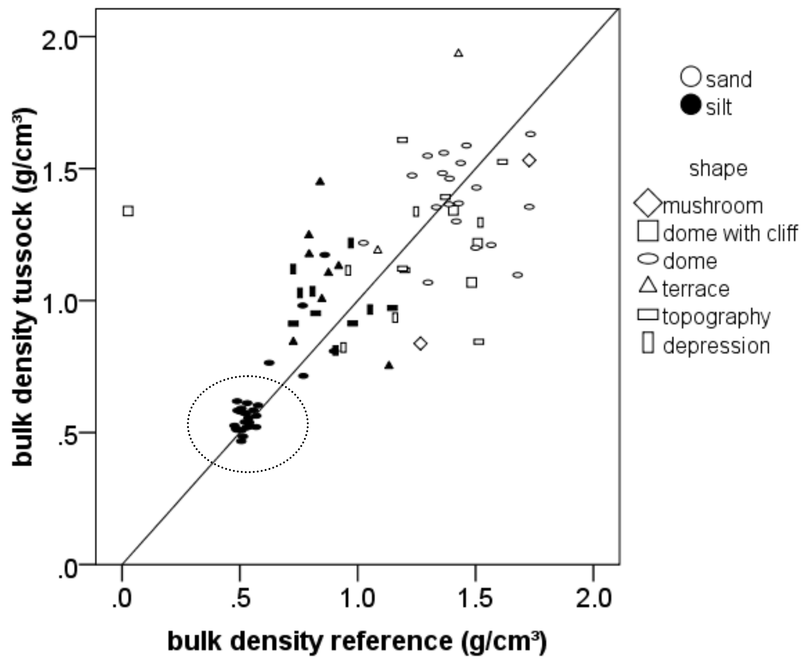


Fig. 8.35 Bulk density: tussock to reference. All tussocks (N=83), circle indication Tollesbury. Freeze dried sediment.

Fig. 8.36a shows the silt content (< 63µm) of all tussocks labelled by its shape. 53 tussocks are situated below the diagonal line and 30 tussocks above. All terrace shaped tussocks are situated below that line meaning that the silt content of the reference sample is higher than within the tussock. This hints to higher turbulence within the vegetation which is likely to be the reason for the terrace shape. Silt content is higher in the vegetation for most of the cliffed and mushroom shaped tussocks because the tussocks developed some years ago and the conditions around it became harsher during the last time causing the erosion around the tussock.

For dome shaped tussocks and for tussocks in a depression no clear trend is found, the dots are equally distributed along the line. Tussocks following the topography also tend to have lower silt contents in the vegetation like terraced tussocks, this could mean that both shapes develop due to the same process.

In total the silt content at the reference point seems to be higher than that of the tussock when 50% silt content is exceeded.

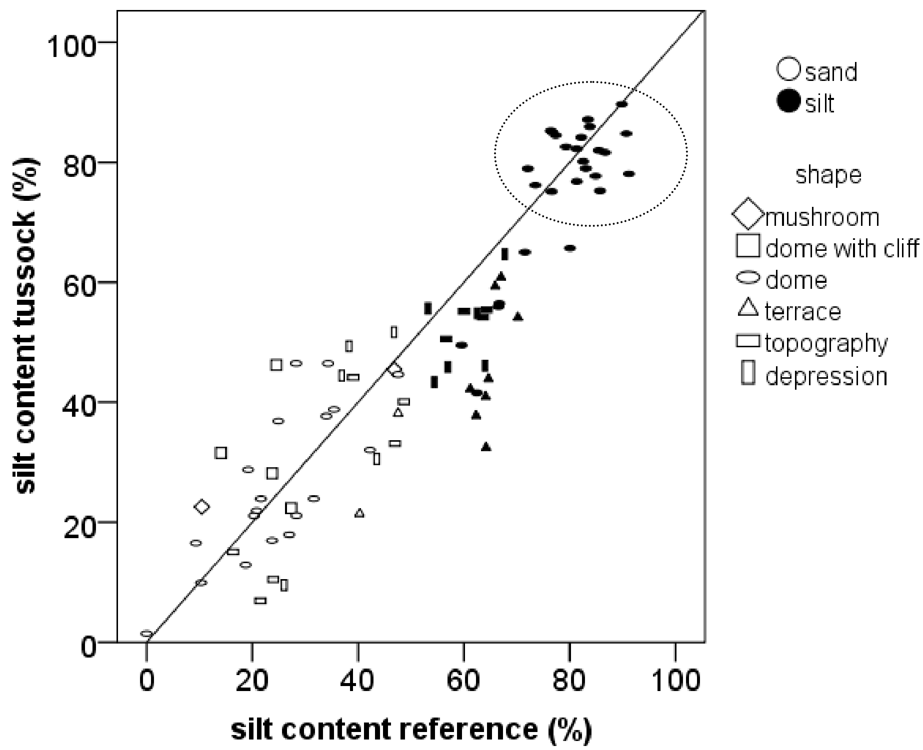
Mushroom and dome shaped tussocks with a cliff are only found at sandy sites, all other shapes exist at sites with sand or silt.

The spread of the grain size analysis is remarkable because of the complex system and inhomogeneity. The processes are complicated and only the comparisons of different shapes reveal a certain pattern. But this pattern is only proving that grain size of the tussock is for some shapes bigger than its surrounding and no evidence for smaller grain size due to sedimentation was found.

The analysis of the wake zone sediment samples (only for Westerschelde, at some tussocks no wake zone was sampled because of overruling micro topography) showed a clearer trend. Up to 50-60% silt content the wake zone has finer sediments than the reference sample above 60% it gets unclear (Fig. 8.36b).

This reveals that at high currents (sandy spots) the tussock causes significant flow reduction behind it (seen from the water side) whereas at sheltered sites the flow obstruction is not visible in the sediment composition. The median grain size shows similar pattern but the bulk density is equally spread although grain size and bulk density of the wake zone are correlated (Pearson: 0.735, 0.01 level).

a)



b)

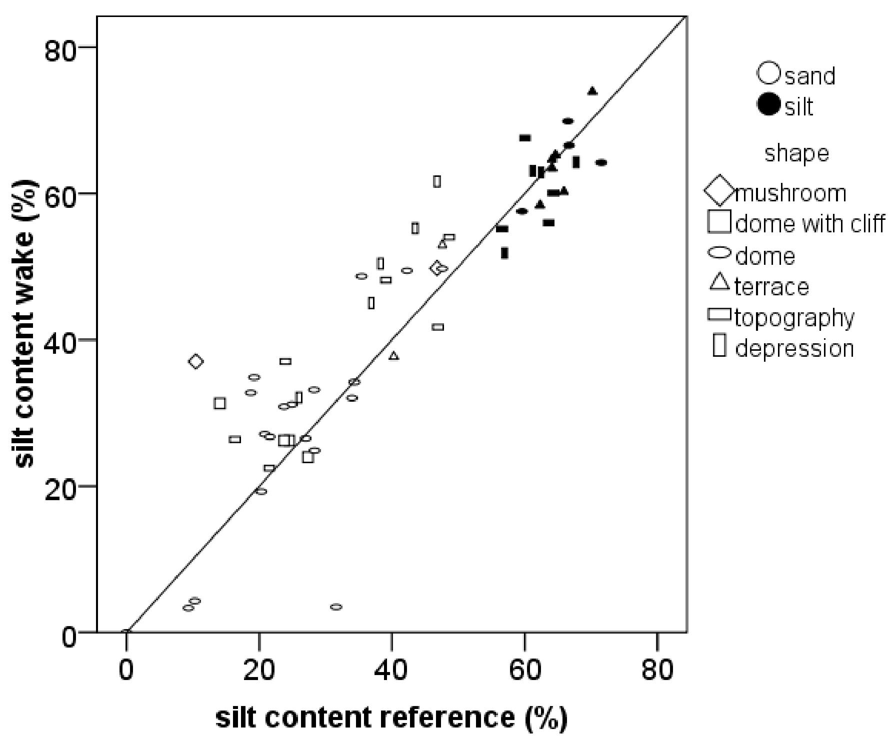


Fig. 8.36 Silt content comparison

a) tussock and reference: all tussocks (N=83), circle indicating Tollesbury

b) wake zone and reference: only Westerschelde, only where distinct wake zone is present (N=55)

A T-test is carried out to prove that grain size and silt content differs between reference vegetation and wake zone for tussocks in high energy and low energy environments at the Westerschelde.

Therefore the tussocks were divided in two parts, one with the reference sample in the silt fraction (silt) and one in the sand fraction (sand).

The T-test shows for which category the median grain size and the silt content is significantly different. By subtracting the reference value from the tussock or wake value a significant difference would result in a confidence interval which is completely below or above zero.

The table (Fig. 8.37) supports what was already shown in the previous graphs, “silt” tussocks have a significantly lower silt content in the vegetation and therefore a higher median grain size (D50). The bulk density is not higher in the vegetation as it would be expected due to the coarser sediment, therefore the vegetation strictly speaking the roots must have an effect on bulk density.

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
(silt) silt % tuss minus ref	-5.0214	44	0.0000	-6.9027	-9.6732	-4.1323
(sand) silt % tuss minus ref	-0.1531	37	0.8792	-0.2557	-3.6405	3.1290
(silt) D50 tuss minus ref	3.7892	44	0.0005	6.5164	3.0505	9.9824
(sand) D50 tuss minus ref	-0.4137	37	0.6815	-1.5155	-8.9380	5.9069
(silt) silt % wake minus ref	-1.6927	17	0.1088	-1.8981	-4.2641	0.4678
(sand) silt % wake minus ref	3.0764	36	0.0040	4.6348	1.5793	7.6903
(silt) D50 wake minus ref	-1.4815	17	0.1568	-2.9276	-7.0968	1.2416
(sand) D50 wake minus ref	-0.8737	36	0.3881	-3.7882	-12.5817	5.0053

Fig. 8.37 T-test of median grain size (D50) and silt content distribution

The results stand in contrast to the theory that tussocks have a higher silt content within the vegetation compared to the reference sample which could be explained due to turbulence within the tussock.

Significant is also the higher silt content in the wake zone of “sand” tussocks compared to the silt content of the reference sample.

As shown for tussocks at Zuidgors and Hoofdplaat this elevated wake zone likely develops when the turbulent flow leaves the vegetation patch, resulting in a lower energy level, which is demonstrated by the coarser sediment within terrace shaped tussocks. It was also found in the field that holes in the dense tussock vegetation show sedimentation of fine sediments.

8.7 Vegetation properties

The analysis of average stem height and stem density as an indicator for physiognomy and vigour of the tussock does not give many clear results.

Although it is known that especially the stem density has an effect on sedimentation and erosion processes around and within Spartina anglica tussocks (BOUMA et al. 2009) no relations between stem density and height, shape, sediment grain size or dome volume where found. This was already clear for the Westerschelde because of the dominating large scale effects.

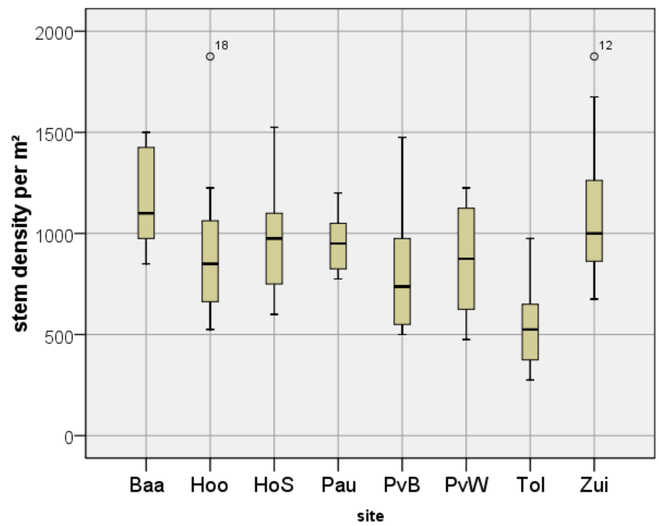


Fig. 8.38 Stem density site comparison

In total the stem density is highly variable between 500 to 1500 stems per m², only the tussocks at Tollesbury have a lower stem density compared to the others (Fig. 8.38). This can have many reasons like different genome variety, different climate or the very fine sediment.

Moreover the stem height does not show any regularity while looking at different sites, it ranges between 10 and 80 cm because some exposed tussocks were nearly destroyed. However at Tollesbury a positive non-linear relation between tussock size and stem height was found. Because the sediment within the patches at Tollesbury showed clear oxidation whereas the surrounding sediment was very poor in oxygen (black colour from 5mm depth onwards) this process could explain the positive relation between size and stem height.

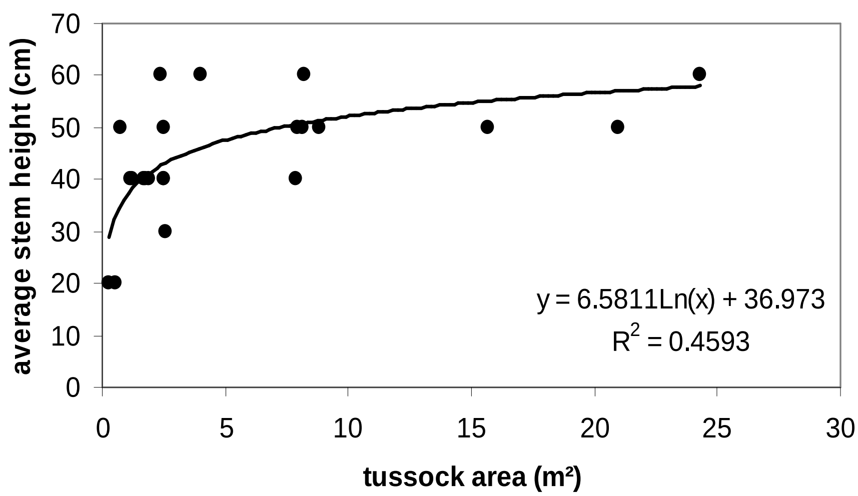


Fig. 8.39 Stem height to size at Tollesbury

Because there is no relation between tussock size or stem height and basal elevation of tussock to hydrographic zero, a decrease of inundation stress is not the explanation. It was found for the tussocks at the Westerschelde and Tollesbury that also the growth rate is a function of tussock size, therefore this variable seems to be very important.

8.8 Conceptual model of high energy tussock development

Because of its complexity an all-encompassing model of tussock development would go beyond the scope of this thesis. To cover the most clear situations two different excel models based on the derived correlations from the data were made to understand tussock development under certain conditions.

The tussock height difference to tidal flat elevation change graph of the two most extreme eroding and accreting sites (HoS, Zui; Fig. 8.32) builds the base for this conceptual model for exposed tussocks. The Pearson correlation is 0.889 at the 0.01 level. Because it is unknown how long it takes to reach the height difference under these conditions a time span of 5 years is set in which the tussocks reach their shape.

Equations:

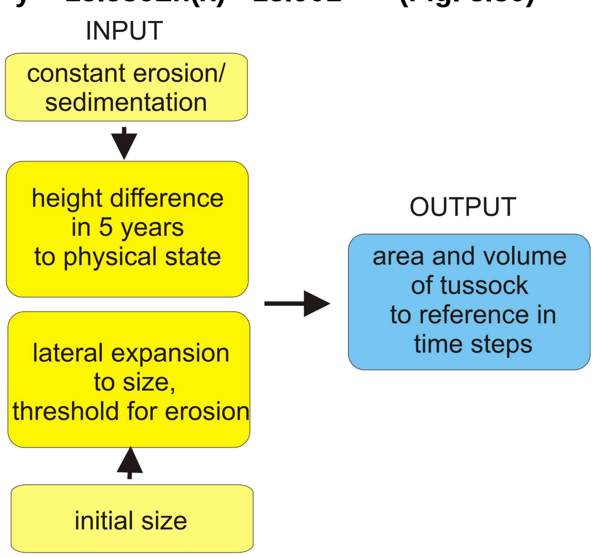
Height difference in cm (tussock to reference after 5 years) as a function of constant erosion or accretion of tidal flat in cm per year:

$y = 0.0757x^2 - 2.1544x + 8.0053$ (Fig. 8.32)

Lateral expansion rate in cm/year to tussock size in m²

If tussock to flat <20cm than: If tussock to flat >20cm than:

$y = 15.536\ln(x) - 18.901$ (Fig. 8.30) **y = -5 cm/year**



The input variables which can be set in the excel model are a constant sedimentation or erosion rate of the tidal flat and the initial size of the tussock.

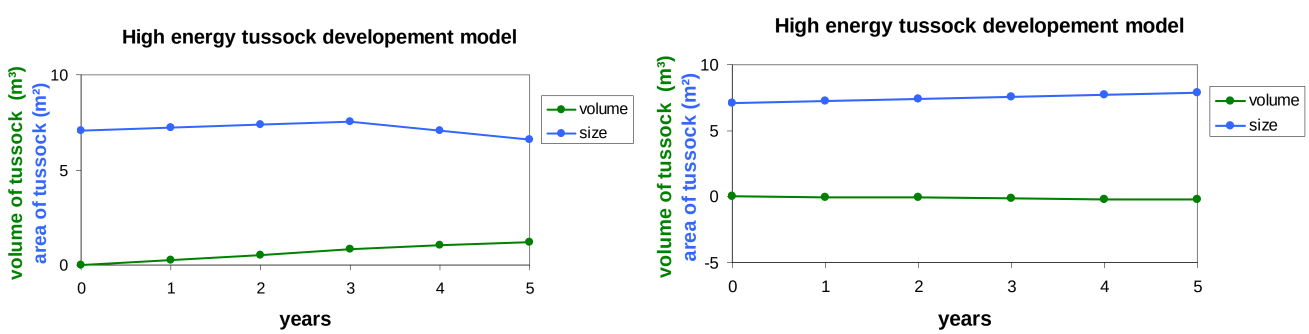
The volume is calculated from height difference and size of tussock with the geometric formula of a paraboloid.

Different geometric shapes of the tussocks can not be included.

$$V = \frac{\pi}{2} \cdot r^2 \cdot h$$

Fig. 8.40 High energy tussock model

The results show how two tussocks of the same size would develop according to the model (Fig. 8.41). In an eroding environment the tussock would grow size dependently until the height difference is too big, from that point on it is eroding in a constant way. The volume instead is still increasing because the surrounding sediment level is dropping continuously. In an accreting situation the tussock would grow size dependently whereas the volume becomes negative compared to its surrounding.



10cm/year erosion, 150cm radius

10cm/year accretion ,150cm radius

Fig. 8.41 Results: high energy tussock development model in eroding (left) and accreting environment (right). Tussock in eroding environment starts to shrink when 20cm elevation is exceeded.

8.9 Conceptual model of low energy tussock development

This model is meant to predict the dome volume and size of tussocks which are situated in a slowly accreting and sheltered environment like Tollesbury.

Therefore the correlation between dome volume and size which was found for Tollesbury is building the base of this model (Fig. 8.28). Because no difference between dome shape and sedimentation rates at Tollesbury was found and the sedimentation rates range from 0.425 to 2.26 cm/year this model is valid for accretional situations within this scale. The lateral expansion rate is always positive and is described with the same size dependency as above.

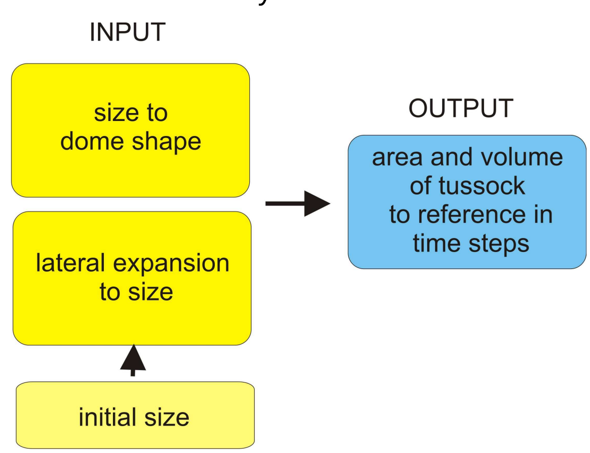


Fig. 8.42 Low energy (accreting) model

Equations:

Expansion as a function of size:
y = 15.536Ln(x) - 18.901 (Fig. 8.30)

Dome volume as a function of size:
y = 0.067x - 0.0779 (Fig. 8.28)

The input for this model is the initial tussock size. The output is the development of size and dome volume of the tussock in time steps.

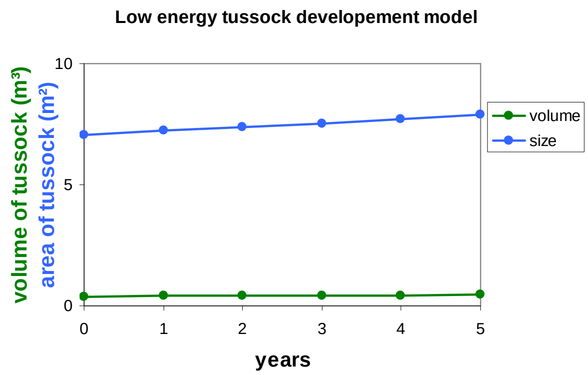


Fig. 8.43 Results: low energy tussock development model in accreting environments between 2 and 5 cm per year.

8.10 Net volume of tussocks and their surrounding

The volume analysis which is described in chapter 7.1.2 is one of the biggest advantages of the DGPS measurements and was already used to determine the exact dome volume.

By including the area of 1m around the vegetation edge also the volume of a possible gully can be considered and therefore the overall ratio of sediment above and below the reference plane. This analysis is interesting for coastal protection issues as it gives the net sediment volume of a tussock and its surrounding compared to a reference.

It tells us if the amount of sediment which is kept due to vegetation presence is bigger or smaller than the loss of sedimentation around or within the tussock due to turbulence and enhanced flow (BOUMA et al. 2007, VAN HULZEN et al. 2007).

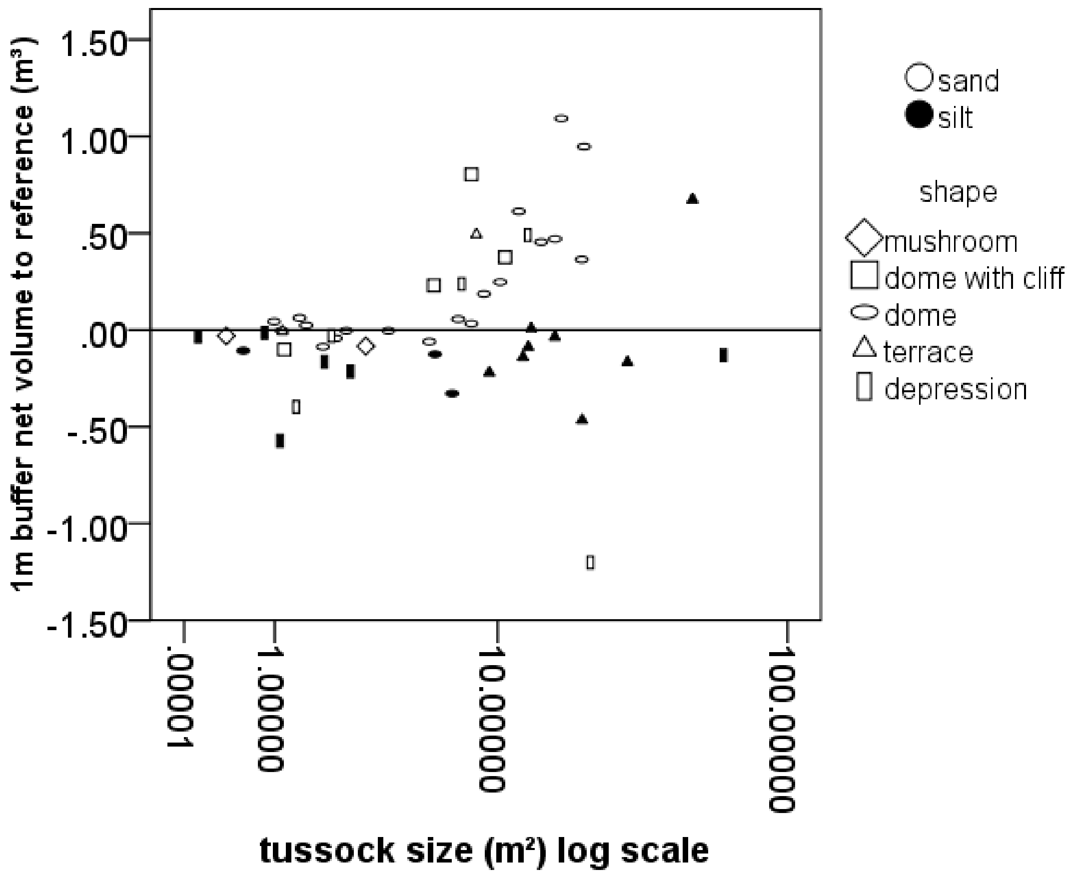


Fig. 8.44 Net volume of all tussocks at the Westerschelde (category topography excluded) The area within 1m distance of the tussock edge is included to estimate the negative effects of scouring around the tussocks in contrast to the elevated tussock.

Because tussocks which are flat follow the topography of the salt marsh or tidal flat they have been excluded from this analysis, the results would show numbers which refer to the general topography and not the tussock induced elevation difference. Tussock 14 is excluded because it is too big for the graph and considered as an outlier.

Fig. 8.44 shows that for tussocks up to 6m² the size the ratio of positive to negative volume is close to zero.

This negative ratio is continuing for bigger tussock in silty areas whereas bigger tussocks at sandy areas create a positive volume ratio.

The negative ration is mainly caused by terrace shaped tussocks (Hoo, Zui) because they have deep scouring especially in front of the tussock.

The positive volume ratio is caused by unbalanced dome shaped tussocks and cliffed tussocks which bind a lot of sediment whereas their surrounding is dropping.

Gullies do not occur regularly at those tussocks and therefore the balance is positive.
Tussocks in a depression can cause both, positive and negative ratios, depending on the elevation of the wake zone and the depth of the depression.
All tussocks at Tollesbury would show a positive ratio because they do not have any gully formation. Their volume is already shown in figure 8.26.

9 Conclusion

Hypothesis (1): Tussocks have different shapes i.e. topography which depend on their environment.

This study shows that the theory of dome shaped sediment trapping tussocks due to enhanced sedimentation is only partly true.
In fact the overall sediment dynamics are causing bigger differences in Spartina anglica tussock topography.
Sediment trapping occurs only at sites with very low hydrodynamics and hence muddy sediment. Most dome shaped tussocks at the tidal flats (shoals) of the Westerschelde have a higher elevation because the erosion around the tussocks overrules the sedimentation within the tussock. The low energy type of dome shape in an accreting environment is named “balanced domes” whereas the dome shaped tussocks in erosive high energy environments are called “unbalanced domes” which can result in cliffed and mushroom shaped tussocks if erosion is continuing rapidly.
Turbulence seems to play a major role at sites where tussocks have to face high current velocities and no erosion is occuring. At accreting sites with high current velocities tussocks stay flat because turbulence prevents sedimentation whereas the wake zone of those tussocks is elevated due to enhanced sedimentation when the turbulence breaks down while leaving the patch.
The wake zone of the patch has a different sediment composition at sites with fast currents if the erosion around the tussock is not too high. This could have a facilitating effect on seedling establishment. At muddy sites this effect is missing, but an effect is visible within the patch resulting in 4-10 % less silt content of the sediment compared to its surrounding.

Gullies which are considered to hinder lateral expansion are not a regular feature of elevated tussocks or of particular shapes but occur most likely at eroding sites and indicate rough conditions. To say in what extend they hinder expansion or if just the erosion around the tussock is stopping the tussock from growing a repeated measurement in 2010 would be needed. This would also show if tussocks have a preferred direction in which they expand e.g. in the direction of the wake zone. Especially the situation at Hoofdplaat is suitable to observe if tussocks have a preferred direction of expansion. This site would be also appropriate to answer if and how tussocks merge to a continuous sward.

The described small scale differences emphasize that the dewatering channels play an important role in tussock development. Tussocks can induce channel erosion but they can also be modelled or destroyed by it, this topic deserves more attention to predict the future of patchy vegetation in tidal environments.

The Plaat van Walsoorden shows that also large scale sediment dynamics can have spatial patterns which influence tussock growth or erosion in short periods overruling all other processes.

The ability of tussocks to bind sediment and therefore prevent it from erosion results in a positive balance of sediment volume which is kept compared to the scouring around the tussocks. If tussocks develop to mushroom shapes the scouring gets to big to sustain a positive balance. These extremely elevated tussocks must have an effect on a larger scale. The rather dense ensemble of several cm elevated mushroom and dome shaped tussock at the eroding site of Hooge Springer can either enhance the erosion of the whole tidal flat due to scouring or mitigate erosion because the structures reduce the overall velocity. It will be interesting to see how this site develops.

Hypothesis (2): Tussock development (expansion, erosion) is different between different shapes.

Elevated tussocks in high energy environments are likely to erode when they exceed 20 cm height difference to its surrounding. However, it is not clear if the height difference below 20cm or the slope of the tussock edge is significantly influencing the lateral expansion rate. Tussocks which were growing on the long run have a significantly size dependent growth rate not depending on height differences.

This has either a self induced reason because bigger tussocks create more favourable conditions or it is due to the fact that bigger tussocks are always situated at more favourable locations and therefore grow faster.

As described in the literature tussock expansion is highly variable in space and time and might be also a result of seasonal temperature differences which is worth to investigate for the Westerschelde.

Especially with new “on the fly geo- corrected” aerial photographs further analysis of tussock development with GIS is a recommended task for further research to asses the development of patchy Spartina anglica vegetation.

Hypothesis (3): Spartina reaches its limits of ecosystem engineering under extreme conditions.

With transferring the results to the theory of ecosystem engineering it becomes clear that S. anglica tussocks are not always able to influence its habitat positively. Only tussocks at low energy accreting environments enhance sedimentation and therefore increase the surface height which leads to less inundation stress and better drainage. At exposed accreting sites sedimentation only takes place behind the patch leading to positive feedbacks whereas the tussock itself is not elevated or even situated in a depression with tendencies to negative feedbacks.

Many tussocks in stable environments where no sedimentation or erosion takes place do not seem to have any effect.

Tussocks at exposed and eroding sites only delay the erosion process due to sediment binding of the roots which leads indeed to a higher elevated tussock compared to its surrounding but this is not true ecosystem engineering. It still has an effect on its abiotic environment but will not change it in the long run, the effect will always remain within the isolated patch. In general the large scale sediment dynamics seem to influence the tussock development in dynamic environments more than the vegetation patch itself.

The effect of large scale sediment dynamics around patchy vegetation is also likely to have an effect in other dynamic environments.

The shape of Nebkha dunes in the deserts for example is likely to be influenced by the changing sediment level around the Nebkha (WANG et al. 2008) which can have effects on the vegetation of the Nebkha and on soil properties. Similar structures to Spartina tussocks are also occurring in semi-arid rivers where reed (*Phragmites mauritianus Kunth*) forms dome shaped clonal tussocks (KOTSCHY and ROGERS 2008). With seasonal changes of dry and wet periods this is an even more complex system where overall sediment dynamics can play a major role in describing how the patch will develop.

With alternating climate and human activities coasts and deserts are facing similar changes and threats today and in the future. Sediment dynamics will change with the sea level, storm activities and precipitation in estuaries and along coasts and also with the wind system and alternating precipitation regimes in deserts. It is important to know how the vegetation in these sensible environments will react on these large scale changes in terms of ecology and in terms of coastal protection and desertification.

10 Recommendations

Next to this analytical approach and the already mentioned possible continuative work also experimental research will be needed to complete the knowledge about the dynamics of Spartina spp. patches.

The crucial question if hydrodynamics hinder lateral expansion can be answered by simply blocking out hydrodynamic forces in situ.

A clever design of brushwood pushed into the sediment around the tussock (like a sedimentation field) in a certain distance would be able to dampen waves and currents. It is expected that those tussocks will grow faster than adjacent tussocks or the same tussock in the year before. This and also the change in topography can be easily measured with a DGPS. Tussocks in a depression and the scouring of terrace shaped tussocks would be expected to get filled. A problem could be to control the scouring which is caused by the construction therefore a certain distance to the tussock will be needed. Suitable sites would be Hoofdplaat, Paulinapolder (east) and Zuidgors.

Another missing link is the climate and weather effect on Spartina anglica.

Simple growing experiments should be able to derive conclusions about sensitivity to frost and preference of warmer temperatures of this C4 plant. Also the problem of water logging could be quantified with growing experiments.

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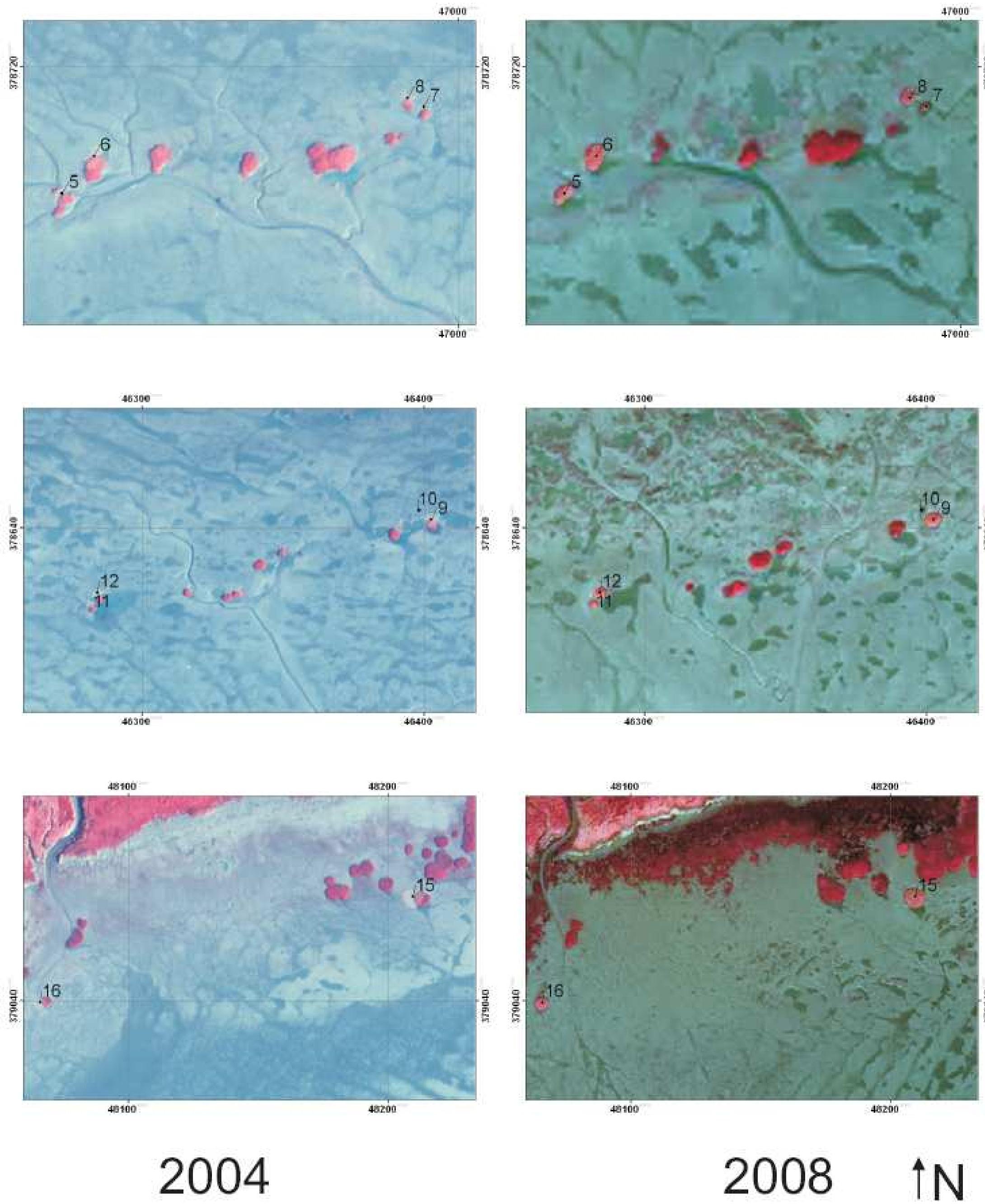
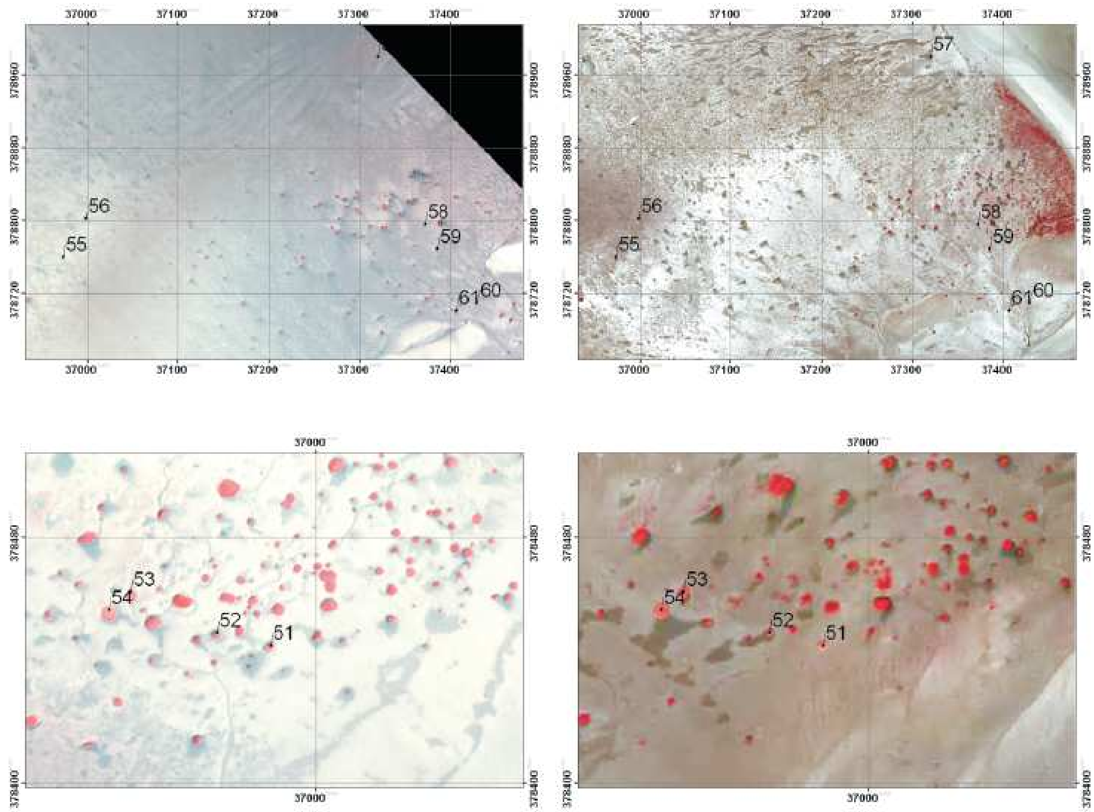
12 Addendum: Tussock development 2004-2008

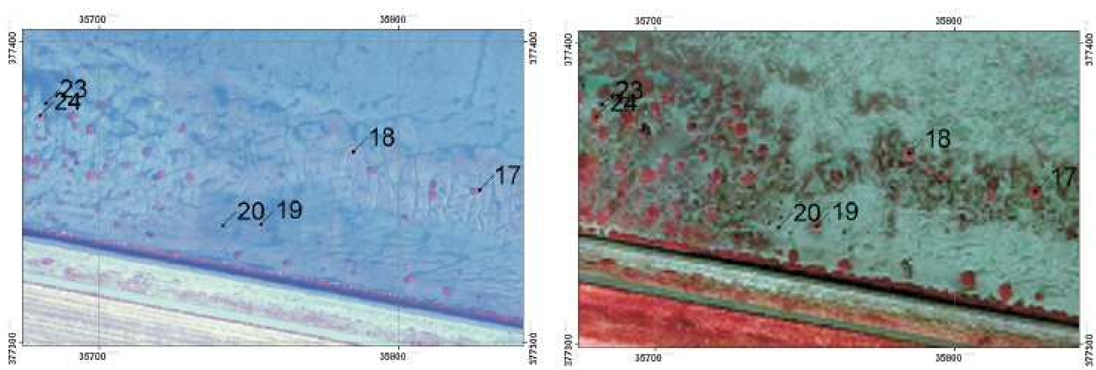
Development of Zuidgors



Development of Hooge Springer

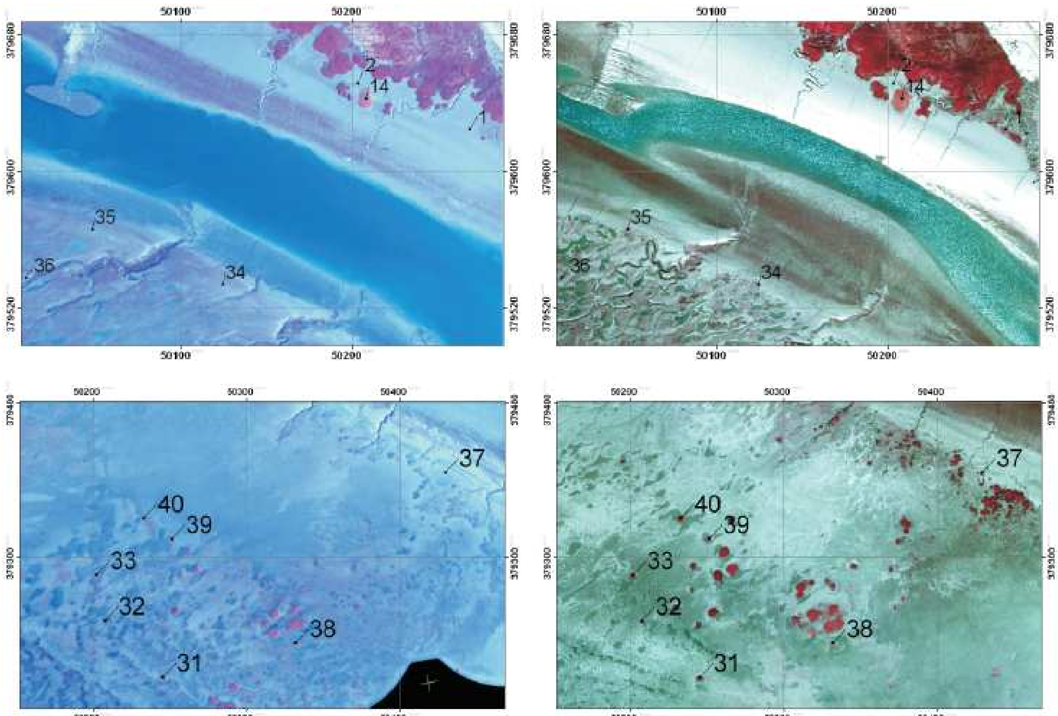


Development of Hoofdplaat



2004 2008 ↑N

Development of Baarland



2004 2008

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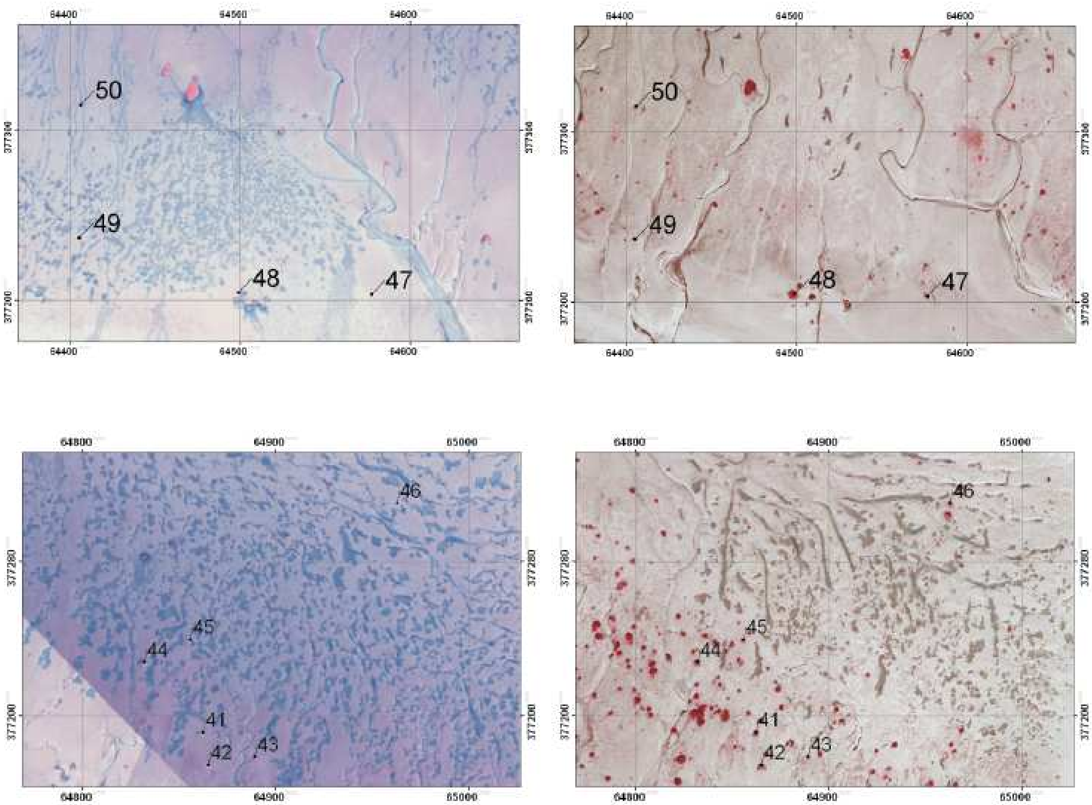
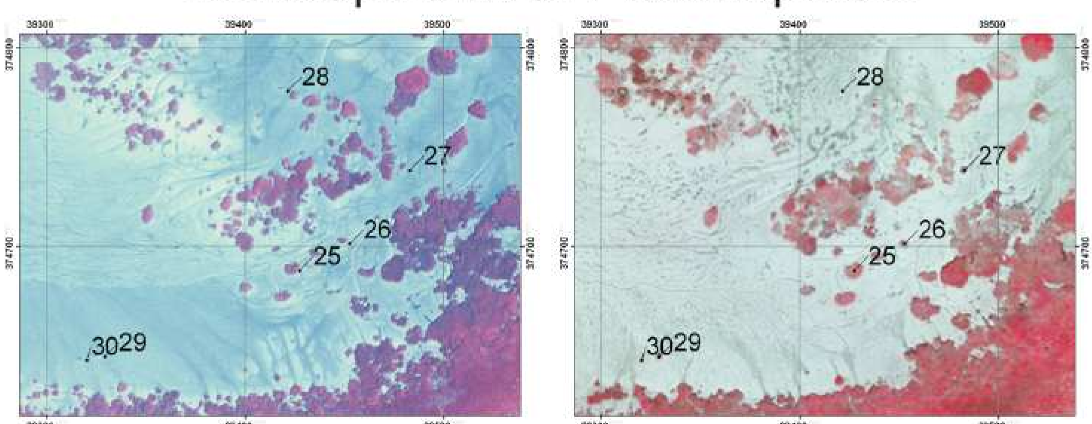
Development of Walsoorden



Development of Paulinapolder



2004 2008 ↑N

13 Data CD

This CD contains GIS data and photos of all 83 tussocks at Tollesbury and the Westerschelde.

14 Acknowledgments - Danksagung

I would like to thank Paul Klaassen and Tjeerd Bouma for excellent supervision of this thesis during the whole period. Also Daphne van der Wal and Annette Wielemaker for support in terms of GIS and reviewing and the whole staff of the NIOO-CEME in Yerseke.
Furthermore I thank Angus Garbutt from the Centre of Ecology and Hydrology in Bangor (UK) and Martin Stock from the National Park Schleswig-Holsteinisches Wattenmeer for support during the fieldwork.
Additional data was provided by the Environment Agency (UK) and Rijkswaterstaat.

Ein besonderer Dank gilt meiner Freundin Carmen für die Unterstützung und Geduld während der letzten Monate und besonders während der sehr kurzen Wochenenden. Nicht zuletzt danke ich meinen Eltern die mich stets gefördert haben und die vieles erst möglich gemacht haben.

ERKLÄRUNG

Hiermit erkläre ich an Eides Statt, dass ich die vorliegende Arbeit selbst angefertigt habe; die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht.

Die Arbeit wurde bisher keiner Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht.

Hannover und Yerseke, im April 2009

Thorsten Balke