Growing with sea level rise - Deltaprogram Wadden Progress Report inventory mussel beds 2011: Cluster 3 Sediment

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Summary

Mussel beds are important bio-stabilizers that can shape marine ecosystems. Nowadays mussel beds often consist of blue mussels (*Mytilus edulis*) and Pacific oysters (*Crassostrea gigas*). Both blue mussels and Pacific oysters filter particles from the water column and deposit those underneath and near the mussel bed, thereby elevating the sediment underneath the mussel bed and the mud flat surrounding the bed. As a result these bivalve beds form conspicuous structures that can influence tidal flow and wave action and, in doing so, modify patterns of sediment deposition, consolidation, and stabilization. For the Deltaprogram Wadden they offer promising possibilities for sustainable coastal protection combined with high natural values. Until now no information exists on the temporal development in sediment accumulation underneath mussel beds, nor in the actual vertical growth of the bed structure as a result of sediment accumulation. Also the role of the ingrowth of Pacific oysters on the stability of the mussel bed is unknown. This information would contribute to a better understanding of the Wadden Sea system and would feed models which focus on the development of vertical growth in mussel beds. It also contributes to our knowledge of processes affecting tidal flat and gully dynamics in the Wadden Sea in relation to sea level rise. In this report a first inventory is made of the temporal development of the underlying sediment of mussel beds and the effect of the ingrowth of Pacific oysters based on existing historical samples on individual mussel beds and further research steps for 2012 are proposed.

1. Introduction - Growing with sea level rise

The “Delta Programme Wadden” aims at developing policy advise for a resilient Wadden Sea area, resistant against climate change. The goal is to secure sustainable protection against flooding from the sea of (embanked) land and at the same time safeguarding natural values to the potential consequences of climate change, most conspicuously rising seawater level. Flooding and coastal erosion represent serious safety threats along the Dutch coastline, and may become more serious as a consequence of climate change. Presently Wadden Sea dikes are shielded by tidal flats and salt marshes which reduce wave force. Additionally tidal flats and salt marshes offer valuable habitats in the ecological functioning of the Wadden Sea. When the sea level rises and the tidal flats do not grow accordingly, their protective and ecological values may be lost. Blue mussel, *Mytilus edulis,* beds are bio-stabilizers that can catch sediment from the water column and through this support tidal flats to grow with sea level rise. They form conspicuous structures that can also influence tidal flow and wave action and, in doing so, modify patterns of sediment deposition, consolidation, and stabilization. At the same time they constitute valuable and attractive habitats for other marine benthic animals, which in turn are important prey for birds, fish and seals. Supporting the development of mussel beds on tidal flats may offer promising possibilities for sustainable coastal protection combined with high natural values (Figure 1).

Figure 1. The “Growing with sea level rise” principle and the role of mussel beds in this. Fig 1a (left) shows that tidal flats shield our dikes. Figure 1b (central) illustrates that when sea level rises and tidal flats cannot keep up, the flats will lose this function. Figure 1c (right) illustrates that mussel beds can catch sediment from the water column and through this support tidal flats to grow with sea level rise.

1.1 Aim of this study

The study of the development of mussel beds and their influence on tidal flat and gully dynamics related to sea level rise, is a component of Cluster 3 (Sediment) of the Delta programme Wadden. This component aims at the development of a model on wave reduction by biological structures like mussel beds and salt marshes. For this we need to expand our knowledge on the development of sediment underneath mussel beds and on factors affecting the stability of these structures. As a first step we started in 2011 with a literature study on sediment development underneath mussel beds, the development in height and their effect on wave action. We also analysed existing historical samples which were taken on individual mussel beds. With these data we explored hypothesis on the development of sediment underneath mussel beds and on the effect of ingrowth of pacific oysters on the stability of the mussel bed. In this report we will discuss current knowledge and propose new research questions, method improvements and supplements for the specific aim of the Delta program.

1.1.1 Report set-up

In chapter 2 we describe the current knowledge on sediment development underneath mussel beds, the development in height and their effect on wave action in a literature review. In chapter 3 we describe the analyses of the historical samples on sediment and oyster ingrowth in individual mussel beds. We aimed the analysis of the data on two existing hypothesis:

H1: It is hypothesised that a mussel bed after first settlement consists of blue mussels on a thick layer of very fine silt. After some years the amount of dead shell fragments and sandy particles would increase, contributing to growth in height which might be able to help tidal flats to keep up with sea level rise.

H2: It is hypothesised that invasion of other shellfish, such as Pacific oysters, possibly add more stability to the mussel bed. Pacific oysters stick together and form heavy clumps which are firmly anchored in the sediment. In recent years on many individual mussel beds also Pacific oysters grow, sometimes in very high densities, therefor the beds could be identified as mixed mussel-oyster bed. This structure might increase mussel bed stability.

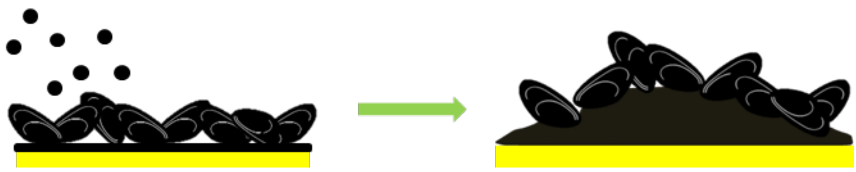
In chapter 4 we discuss the current knowledge based on the literature review and the analysis of the historical data. Thereby we will identify gaps in current knowledge and propose next steps in this component of the Deltaprogramm Wadden.

Figure 2 Mussel beds can accumulate large amounts of sediment and form conspicuous structures in their surroundings.

2. Literature review on sediment development in mussel beds and factors influencing stability

2.1. Mussel beds and sedimentation

Mussel beds are sediment receiving, sediment transporting and sediment delivering "super-organisms" of the Wadden Sea area. Blue mussels filter small floating dissolved particles from the water column, both food particles and fine sediment. All suspended particles > 2-5 µm in diameter are completely filtered out by the gills and removed from the ventilation current (Widdows et al. 1979). Faecal pellets -the direct biological product of ingested and passing stomach and gut particles- and pseudo-faeces – not ingested microparticulate material separated and rejected before ingestion- are produced as biodeposits from the ingestible part of suspensions (Hertweck & Liebezeit 1996).



As a result large quantities of faeces and pseudofaeces are accumulated and deposited in and around the mussel bed, mainly consisting of silt wrapped in a thin mucus layer. This changes the sediment composition underneath the mussel bed and in its immediate vicinity and supports local establishment of fine sediment. The structure of the mussel bed and the mucus layer surrounding the silt particles keeps this fine sediment in place, at least temporarily. In addition to the (actively) biologically derived material from the feeding process, suspended inorganic fine-grained material is trapped by the reduced wave action of the rough mussel bed surface, and passively settles down to the bed. Due to these processes mussel beds can accumulate large amounts of sediment, trapped and detained by live blue mussels and dead shells (see Oost 1995 for further details). Mud is concentrated and deposited in places where wave energy is normally too high for physically controlled sedimentation of fine-grained material (< 64 µm) (Flemming & Delafontaine 1994; Hertweck & Liebezeit 1996). Both the active and passive influence of the blue mussels on the complex origin of the fine-grained material are captured in the term 'biodeposition' (Hertweck & Liebezeit 1996). Biodeposition rates of suspended matter promoted by Mytilus can be 40-times the natural sedimentation rates (Widdows et al. 1998). A solid and stable mussel bed might keep up with sea level rise and influence gully patterns and behaviour. Under stormy conditions part of the trapped sediment may be released again and may be transported to salt marshes or be resuspended in the channels surrounding the intertidal flats (Figure 2).

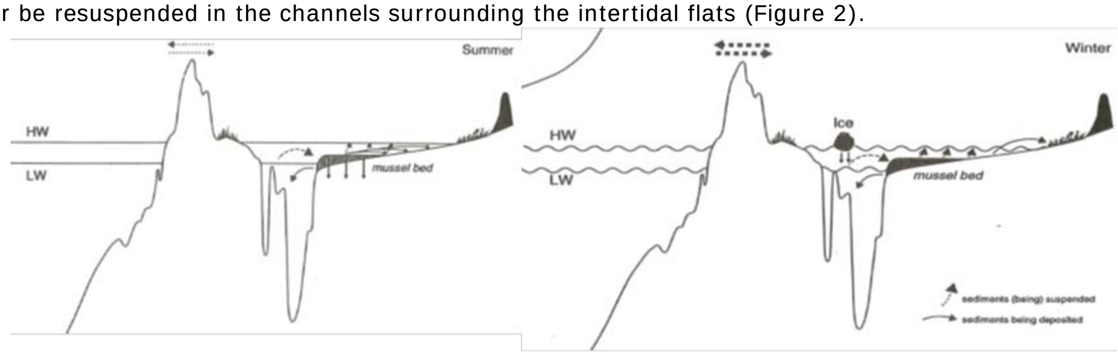


Figure 2. Annual cycle in the sedimentation patterns for fine-grained sediment and the role of intertidal mussel beds in summer (left) and winter (right). Arrows indicate directions and relative magnitudes of sediment transport. Source: Oost 1995.

Figure 3. Over time mussel beds may develop into structures sometimes rising up to one meter from the surrounding intertidal flats, as is shown here by old mussel beds close to the island of Amrum, German Wadden Sea (left) and a mussel bed near Schiermonnikoog (right).

Existing mussel beds in the Wadden Sea can disappear as a result of targeted fisheries, predation by birds and marine animals such as crabs and starfish, storms, changes in water flow and ice conditions (patches of mussel beds may be lifted op by shoals of ice and deposited elsewhere – see Figure 2). However, a stable mussel bed is protected by mechanisms that provide resistance against water flow and storms. They may stick together with byssus threads, by the formation of a solid sediment foundation or by growth of other bivalves as Pacific Oysters which serve as an anchor.

2.1.1. Sediment composition underneath the mussel bed

A typical mussel bed consists of a matrix of alive and dead shells, held together by a network of byssus threads. Underneath, the sediment layer is made up of (pseudo)faeces produced by the blue mussels, sand and other fine-grained material which is settled down, shell debris and organic detritus (Dankers *et al.* 2004).

Filtered material clumps to larger particles and settles down between the shells of the colony. The mussel shells, dead and alive, and their byssus threads prevent resuspension of the disintegrated biodeposits (Oost 1995). The accumulation of biodeposits gradually increases the silt content of the underlying, originally sandy sediment layer (Stoeck & Albers 2000). Investigations of the sediment properties and grain size distributions in and around mussel beds in the German Wadden Sea showed that the mud content (i.e. grain size fraction <63 µm) significantly decreased with increasing distance from the mussel bed towards a sandflat (Figure 4; Stoeck & Albers 2000). In mature *Mytilus* beds, with adult blue mussels of 6-7 cm in shell length, the upper 4 cm of the sediment layer has on average a mud content of ~44%, in comparison with a maximum of 13% in the underlying sediment (Hertweck & Liebezeit 1996).

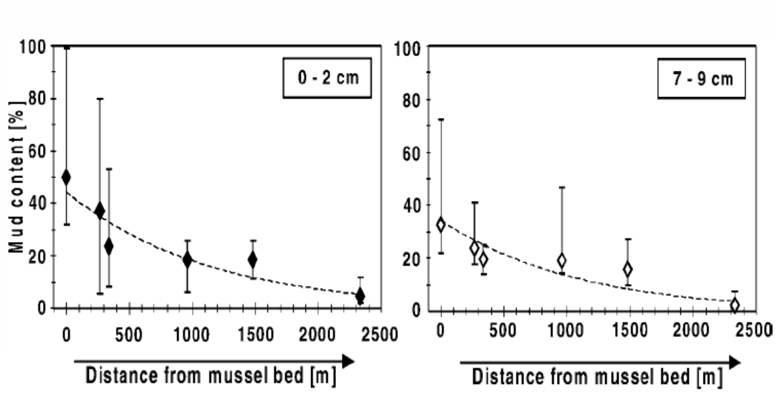


Figure 4 Median values and 95 % confidence intervals (n=9) of the mud content (grain size fraction <63 µm) at the sediment surface (left) and at a sediment depth of 7-9 cm (right) in relation to the distance from the mussel bed. Significant interrelationships between values and the distance were fitted (dotted lines) using an exponential equation (In: Stoeck & Albers 2000).

To prevent being buried under the mud, the blue mussels move up using their foot and releasing byssus threads. In this way they cover the underlying captured mud, and constantly remain at the sediment-water interface for favourable foraging conditions (Oost 1995). The continuous movement of the living individuals creates holes, which are filled with clay, sand and coarser material such as shells and pebbles. This (building) material is mainly transported by waves and captured by the byssus threads of the blue mussels. Sand grains settle down between the blue mussels, which locally results in high sand contents (up to 90% of the grain size > 50 µm) of the older mussel beds (Oost 1995; Dankers *et al.* 2004). The mud consolidates, by dewatering of the sediment, to a solid layer of clay which forms the basis of the mussel bed (Dankers *et al.* 2004).

2.1.2 Height development of mussel beds

The elevation of a mussel bed as a result of net annual biodeposits can vary, depending on biological and physical conditions, from zero to amounts of several centimetres (Flemming & Delafontaine 1994). Young blue mussels are highly mobile and respond to sedimentation by climbing on top of the biodeposited sediment, with observations of 6 cm climbing per day (Van Leeuwen et al. 2010). Due to a combination of upward climbing, the protection of the underlying sediment layer, and high density coverage of the blue mussels, mussel beds are able to capture large amounts of mud. In this way young mussel beds can grow up to 30-40 cm in height in the first half year of their existence (Dankers *et al.* 2004). However, the maximum vertical growth of the mussel bed is restricted by submergence (which means feeding) time, and will hardly ever exceed mean sea level (Van Leeuwen *et al.* 2010).

Established older beds with accumulated sediments can be 1-2 m above the natural surrounding sediment level and have a visible impact on the estuarine morphology (Widdows & Brinsley 2002). In the Dutch Wadden Sea mussel bed reach a thickness of 50-65 cm, compared to as much as 180 cm in the German Wadden Sea (Oost 1995). Hence mussel beds provide an increase of the vertical structure of the mudflats. Even if the living blue mussels are (temporarily) absent the remaining clay layer and shell debris are visible for a long time. These remains are often a good basis for the establishment of new brood (Dankers *et al.* 2004).

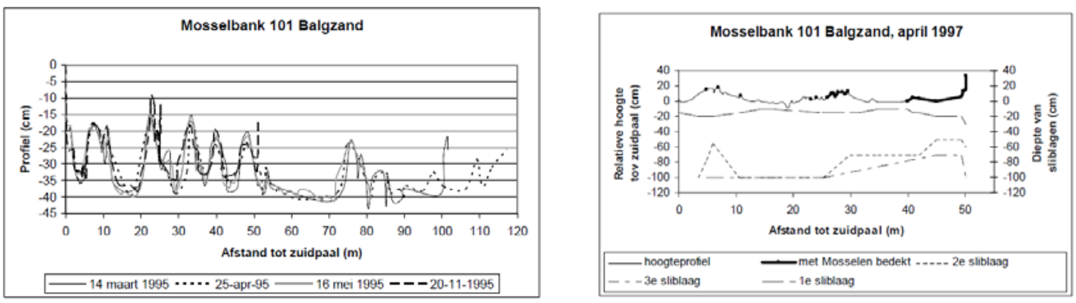


Figure 5 Sediment profile of a mussel bed in the Dutch Wadden Sea, with (left) development of patch height on a fixed transect and (right) the different shell layers underneath the bed.

2.1.3 Stability of mussel beds

Widdows *et al.* (2002) found that erodability of a mussel bed is a function of the nature of the substrate and the density of the blue mussels. After disintegration of the biodeposits the mud becomes more clay-like with cohesive properties, and clay-rich sediments remain. Pelletization changes particle-size distribution and may therefore alter the way of sediment movement (Nowell *et al.* 1981; Groenewold & Dankers 2002). The current velocity needed to erode clay-rich sediments is higher than the velocity to entrain whole pellets (Oost 1995). When the mud is somewhat consolidated, the erosion susceptibility strongly decreases. Mud and mud-sand mixtures are more resistant to erosion than pure sand (Groenewold & Dankers 2002).

Investigations of the erodability of cohesive sediments (46% silt) associated with mussel beds, showed that sediment resuspension declined exponentially with increasing mussel bed density (in % cover; Widdows *et al.* 1998). High mussel bed densities (i.e. 50-100% or more than 1400 mussels per m^2) can reduce sediment erosion by 10-fold with their physical presence on the sediment surface. At blue mussel coverage of ~100%, the bed is more protected by the dense surface layer of blue mussels and the many byssus threads between the individuals, which also prevent any detachment during erosion (Widdows *et al.* 2002).

Erosion of mussel beds can be caused by storms, predation, high current velocities, fishing activities and severe winters with ice coverage of tidal flats (Hertweck & Liebezeit 2002). Half of the young blue mussel beds are lost in the first winter after colonization (Dankers et al 2004). Any reduction in density will make the mussel bed more vulnerable to erosion induced by high current velocities and storms. Widdows *et al.* (2002) describe that a reduction in covering from 100% to 50% will already enhance sediment erosion by resuspension of biodeposits. Though the amount of sedimentation is reduced in consecutive years as a result of lower coverage, mussel beds accumulate coarse sediment and shells over the years. Mud consolidates in clay-rich layers, which results in harder foundation, reducing susceptibility to erosion (Oost 1995; Van Leeuwen *et al.* 2010).

2.1.3.1 Influence of Pacific oysters on mussel bed stability

Pacific oysters are an invasive non-indigenous species. The pacific oyster occurs naturally in marine waters of Japan and south-east Asia. The pacific oyster was introduced into the Dutch Wadden Sea around 30 years ago. In the first years after introduction the population developed slowly. From 1995 onwards distribution and abundance increased rapidly In 1996 a first settlement occurred in the German Wadden Sea area, which may have dispersed from the Netherlands by natural means (Nehring 2003). In 1986 Pacific oysters were introduced in the Northern Wadden Sea at Sylt for cultivation (Reise 1998) and in 1991 the first Pacific oysters were found outside culture plots in the Northern Wadden Sea. At the start of the new millennium it became clear that the Pacific oyster occurred throughout the Dutch Wadden Sea.

Pacific oysters create a hard three-dimensional substrate by forming reefs. They regularly develop in mussel beds. Although Pacific oysters have taken over several mussel beds in the Wadden Sea, nowadays there are also several reports of blue mussel spat settled on Pacific oyster reefs (Fey *et al.* 2010, 2011 van Zweeden *et al.* 2010). Although Pacific oysters can overgrow mussel beds, they themselves form again substrate for blue mussels to settle on. In the end this might result in combined reefs. As Pacific oysters stick together they form large clumps which are anchored in the sediment. Because of this they might positively influence stability of mussel beds.

2.1.4 Influence of mussel beds on water flow and waves

Various biogenic factors are known to contribute to the enhanced near-bed turbulence and vertical mixing in the lower water column, such as bed roughness, bivalve density and bivalve exhalent jets (Widdows *et al.* 2009). Mussel beds interact strongly with the water flow, significantly enhancing surface roughness and increasing turbulent kinetic energy and shear stress above the mussel bed (Widdows *et* *al.* 2009). They form extensive biogenic reefs on lower sediment shores, particularly at the mouths of meso- and macro-tidal estuaries with a good tidal flow (Widdows & Brinsley 2002).

A mussel bed experiences and uses strong tidal currents, which increase vertical mixing and supply phytoplankton in the bottom water (depleted by the filter feeding activity of the blue mussels; Widdows *et al.* 2009). Sediment stability is enhanced by the blue mussels through physical protection of the bed and they influence hydrodynamics via increased friction drag. The roughness of the bed tends to slow down the current velocities close to the bed and generate turbulence (Van Duren *et al.* 2006). Investigations have shown that the friction drag induced by mussel beds, regardless of blue mussel densities between 25-100%, reduces the water flow and the bed shear stress by 25% relative to bare sand (Widdows *et al.* 2002).

Mussel beds and other shellfish reefs could therefore be used to protect e.g. valuable salt marshes from erosion by dissipation of wave energy (Van Leeuwen *et al.* 2010). Recent studies show that salt marshes are able to grow with the sea level rise, provided that sufficient space and sediment is available (De Vries *et al.* 2007). Erosion of salt marshes can be counteracted by realising a gradient of bio-engineers. Blue mussels and Pacific oysters are examples of so-called bio- or ecosystem engineers and provide benefits to coastal and estuarine systems by providing habitat to other organisms, maintenance of water quality and shoreline stabilization. These shellfish reefs provide e.g. coarse material, reduce wave and other erosive energies along marsh and estuarine shorelines (Piazza *et al.* 2005). De Vries *et al.* (2007) investigated that wave action can be reduced by the presence of blue mussels due to energy dissipation, which is caused by the roughness of the bed. However, research also showed that the use of, in this case, Pacific oysters as shoreline protection and stabilization only works in low-energy environments (Piazza *et al.* 2005).

3. Analysis of historical data on sediment development and Pacific oyster ingrowth

3.1 Method

For the study on the development of mussel beds, data were used from 12 existing mussel beds. The data on development of the mussel bed area and the existence of Pacific Oysters for some of these beds date back to 1997. Information on the sediment composition is available for 6 beds from 2003 onwards.

3.1.1 Development of sediment composition underneath mussel beds

To study the development of sediment underneath mussel beds samples were analysed which were taken on 6 mussel beds (502, 503, 603, 606, 607 and 703 – see Figure 6) from 2003 until 2009. The samples were taken with tubes measuring 80 cm long and 7 cm across. From each mussel bed 2 to 3 samples were taken annually, every year on a different location in the mussel bed area (appendix 1).

Location of Mussel beds in this study

Figure 6. Location of the studied mussel beds.

To study the sediment layers underneath the mussel bed, the tubes were cut in half over its total length. The different recognisable layers were described and the colour was registered using Munsell-colour charts (Musell 1912). From every 7 cm section of the core length a subsample was taken. This sediment was freeze-dried and the fraction of particles >5 cm, >2cm en <2cm were weighed. From the fraction of particles < 2 cm the grain size distribution was determined with help of a coulter-counter (Hogg &

Coulter 1947). The sediment was classified according to Atterberg (Keller & Bennet 1973) and described in Table 1.

Table 1. Sediment classification according to Reineck (1982)

Type	**Percentage silt (< 64 µm)**
Sand	< 5%
Silty sand	5-50%
Silty sediment	> 50%

The sediment composition of the samples taken underneath the mussel beds is described in two ways. First of all the particles < 2 mm are classified according to Reineck (1982). Therefor the percentage of particles < 64 µm is calculated for each sample. The Reineck-classification gives insight in the siltiness of the sediment. Secondly the sediment composition is described by means of the shell-content in the sediment. The shell-content of the sediment is presented by the percentage of particles > 5 mm.

3.1.2 Oyster development

From all mussel beds the development of Pacific Oysters was registered by sampling the 'living layer' of the bed. The Oyster coverage was measured by counting the number of Pacific oysters in 1/20 m^2 samples. In each bed 2-5 samples were taken each year. Measurements were taken from 1997 until 2010.

3.1.3 Mussel bed development and cover

From each bed the development in shape and area size was registered each year using a GPS. The coverage in the bed was estimated using the step-method (Brinkman et al. 2003). Within the bed diagonal transects were followed. On each transect the walked steps were counted. Each step with blue mussels was registered as a 'musselstep', each step on bare sediment was registered as a 'sedimentstep'. Every 50 steps a subdivision of the transect was registered. This resulted in sublines within each transects all across the mussel bed with a division in parts covered with blue mussels and parts with open sediment (Figure 7). For each bed the total percentage of 'musselsteps' was calculated, resulting in an indication of the actual cover of that mussel bed. Measurements were taken from 1997 until 2010.

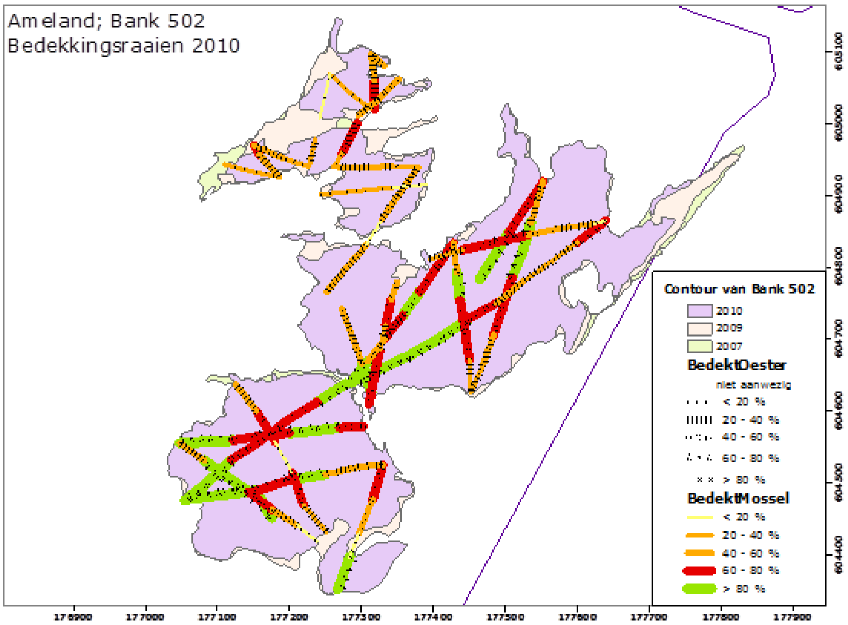


Figure 7 Example of the 'stepmethod'. Within each transect sublines indicate the cover on mussel bed 502.

Figure 8 Pacific Oysters create a hard three-dimensional substrate by forming reefs, influencing the development of gullies.

3.2 Results analysis of historical data

3.2.1 Development of the sediment underneath mussel beds

It is hypothesised that a mussel bed after first settlement consists of blue mussels on a thick layer of very fine silt. After some years the amount of dead shell fragments and sandy particles would increase, contributing to growth in height which might be able to help tidal flats to keep up with sea level rise. In this report a first inventory on this hypothesis is made on the development of sediment underneath mussel beds on the basis of existing historical samples taken on 6 individual mussel beds from 2003 until 2009. The sediment composition of the samples taken underneath the mussel beds is described in two ways. First of all the particles < 2 mm are classified according to Reineck (1982) to get insight in the siltiness of the sediment. Secondly the shell-content of the sediment is presented by the percentage of particles > 5 mm.

Mussel Bed 502 Ameland Molengatplaat

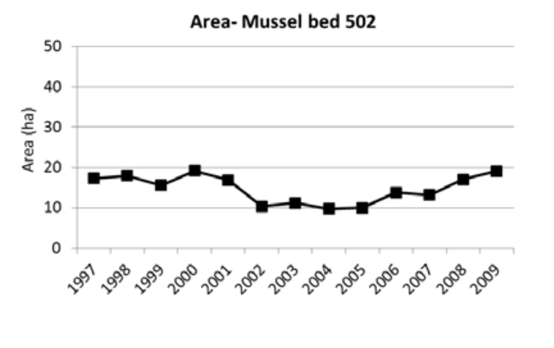


Figure 9 Area of mussel bed 502 from 1997 until 2009

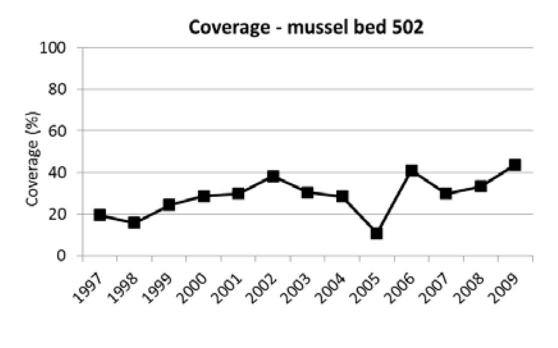


Figure 10 Coverage of mussel bed 502 from 1997- 2009

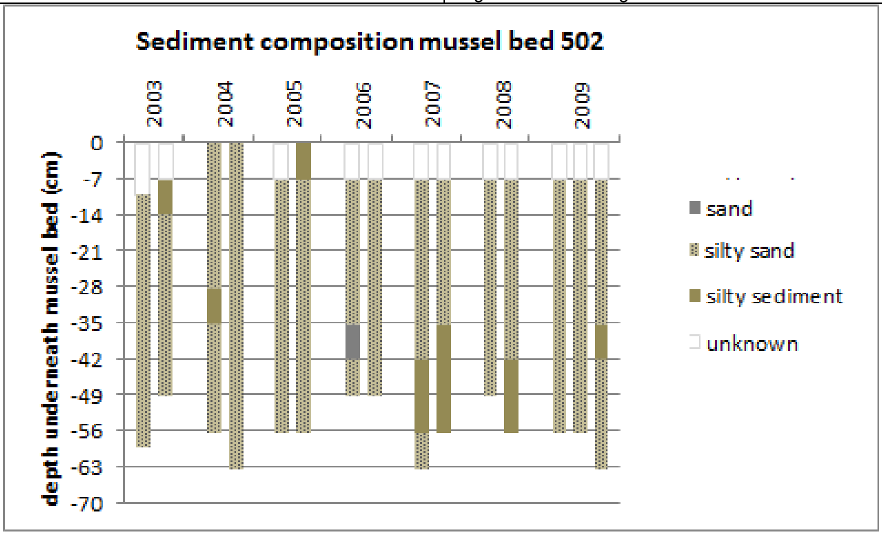


Figure 11 Sediment classification of particles < 2mm (Reineck, 1986). The classification gives insight in the siltiness of the sediment underneath mussel bed 502 from 2003 until 2009

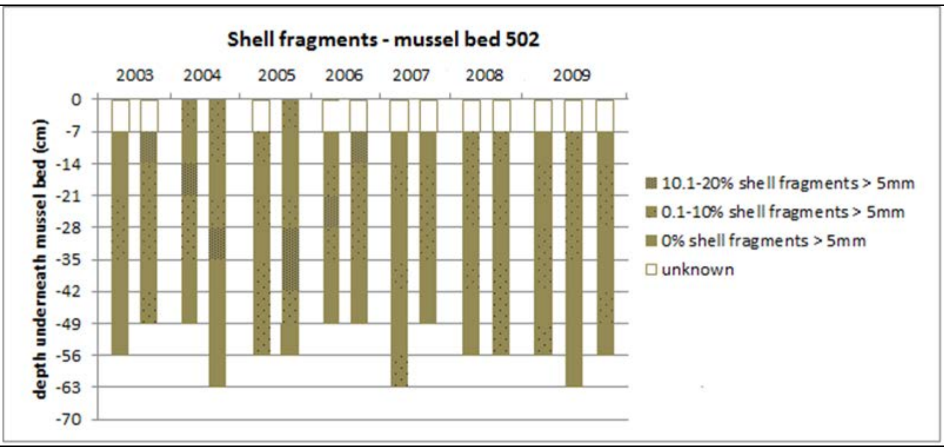


Figure 12 Presence of shell fragments (represented by particles > 5mm) underneath mussel bed 502 from 2003 until 2009

This mussel bed originates from 1994 and was visited in 1995 for the first time. At the start of the sediment measurements in 2003, the bed existed for 9 years. In that time the sediment already consisted mainly of silty sand and in the deeper layers shell fragments of previous years could be found. In 2001, 2002 and 2008 large quantities of young blue mussels fell on the already existing mussel bed, thereby covering older layers. This mussel bed forms a stable structure which exists for already 14 years and covers approximately 20 hectares in 2009.

Mussel bed 503 Ameland Ballumerbocht

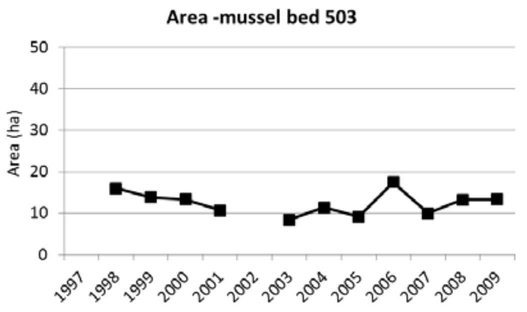


Figure 13 Area of mussel bed 503 from 1997 until 2009

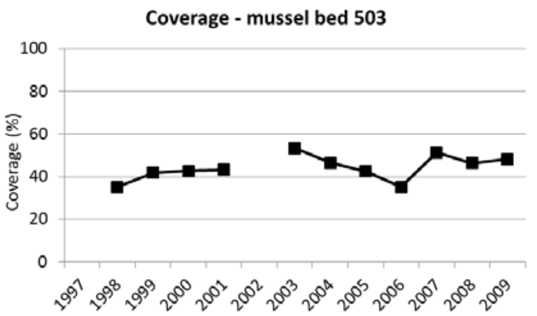


Figure 14 Coverage of mussel bed 503 from 1997 until 2009

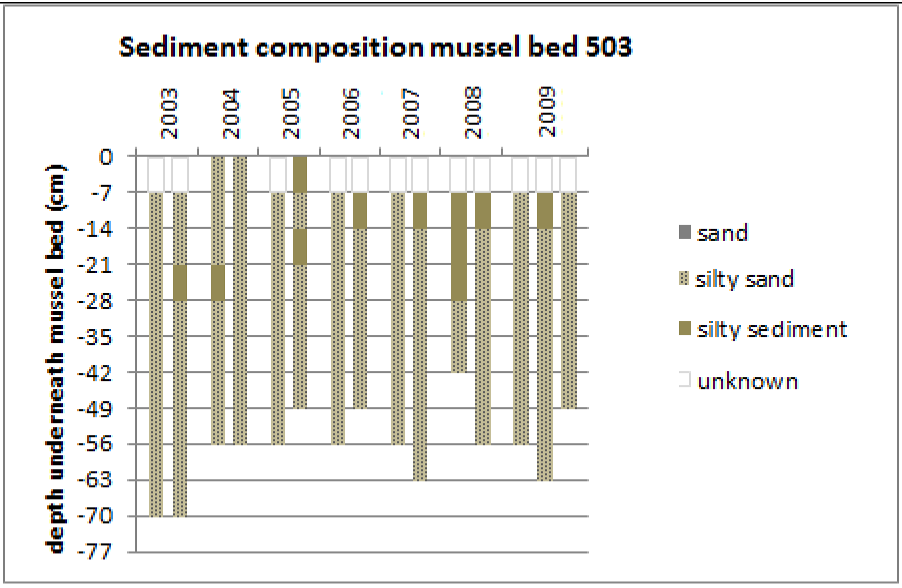


Figure 15 Sediment classification of particles < 2mm (Reineck, 1986). The classification gives insight in the siltiness of the sediment underneath mussel bed 503 from 2003 until 2009

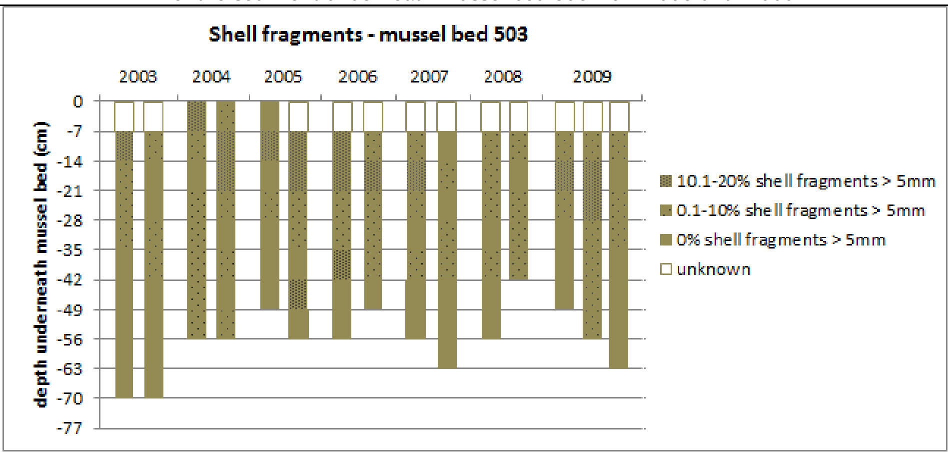


Figure 16 Presence of shell fragments (represented by particles > 5mm) underneath mussel bed 503 from 2003 until 2009

The mussel bed probably originates from 1994, but then eroded by strong storms. In 1996 young blue mussels fell on the eroding bed, restoring coverage. At the start of the sediment measurements in 2003, the bed existed for 9 years. In that time the sediment already consisted mainly of silty sand and in the deeper layers shell fragments of previous years could be found. In 2001, 2007 and 2008 large quantities of young blue mussels fell on the already existing mussel bed, thereby covering older layers. The bed now forms a stable structure of 14 years old.

Mussel bed 603 Schiermonnikoog Brakzand

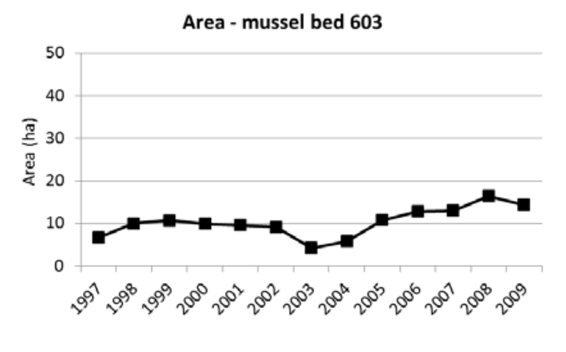


Figure 17 Area of mussel bed 603 from 1997 until 2009

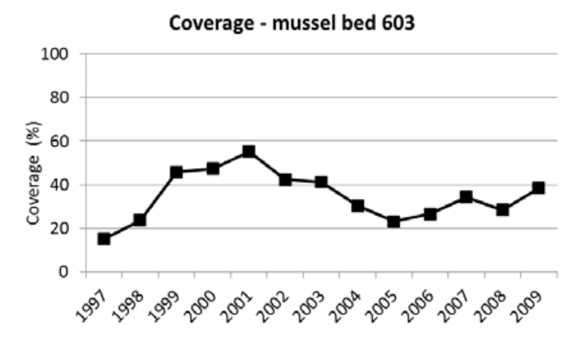


Figure 18 Coverage of mussel bed 603 from 1997 until 2009

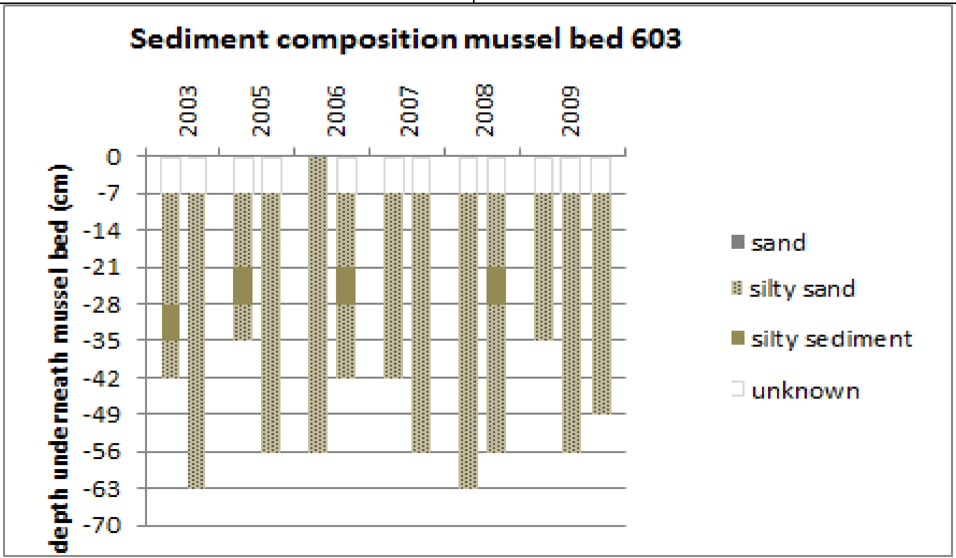


Figure 19 Sediment classification of particles < 2mm (Reineck, 1986). The classification gives insight in the siltiness of the sediment underneath mussel bed 603 from 2003 until 2009

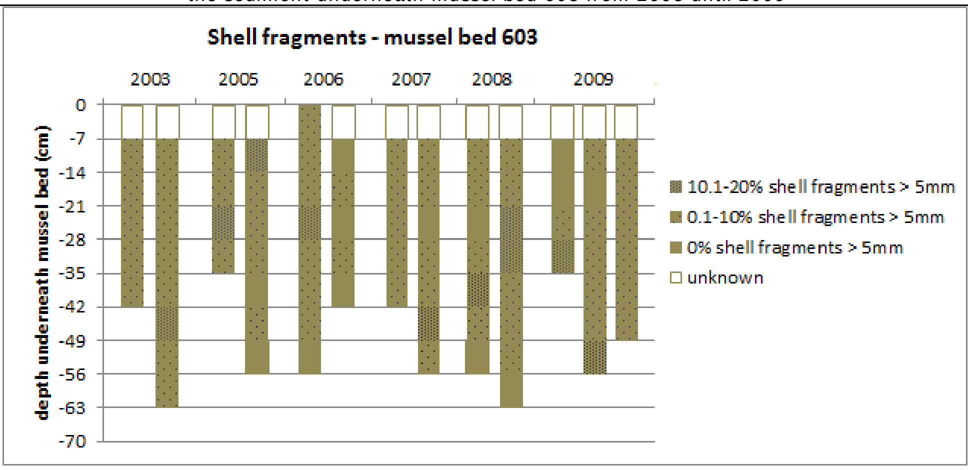


Figure 20 Presence of shell fragments (represented by particles > 5mm) underneath mussel bed 603 from 2003 until 2009

The mussel bed originates from 1994 and was visited in 1995 for the first time. At the start of the sediment measurements in 2003, the bed existed for 9 years. In that time the sediment already consisted mainly of silty sand and in the deeper layers shell fragments of previous years could be found. In 2001, 2002, 2003, 2005 and 2009 large quantities of young blue mussels fell on the already existing mussel bed, thereby covering older layers. The mussel bed forms a stable structure of at least 14 years old and covers about 15 hectares.

Mussel bed 606 Zuid Oost Lauwers Noord

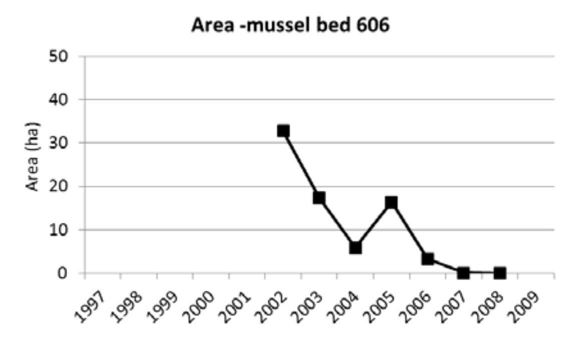


Figure 21 Area of mussel bed 606 from 1997 until 2009

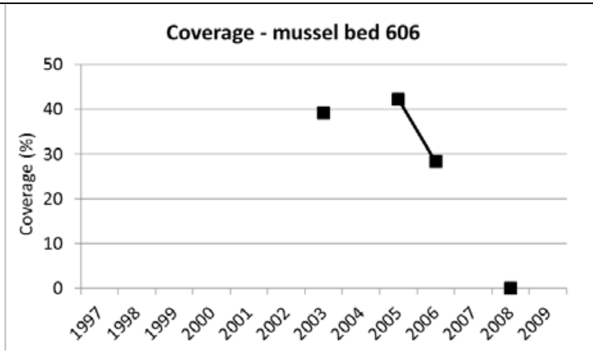


Figure 22 Coverage of mussel bed 606 from 1997 until 2009

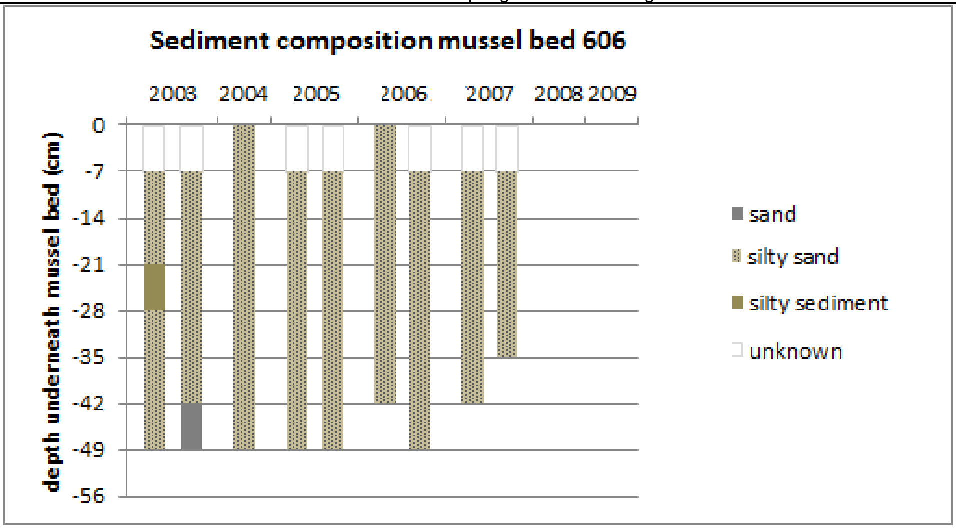


Figure 23 Sediment classification of particles < 2mm (Reineck, 1986). The classification gives insight in the siltiness of the sediment underneath mussel bed 606 from 2003 until 2009

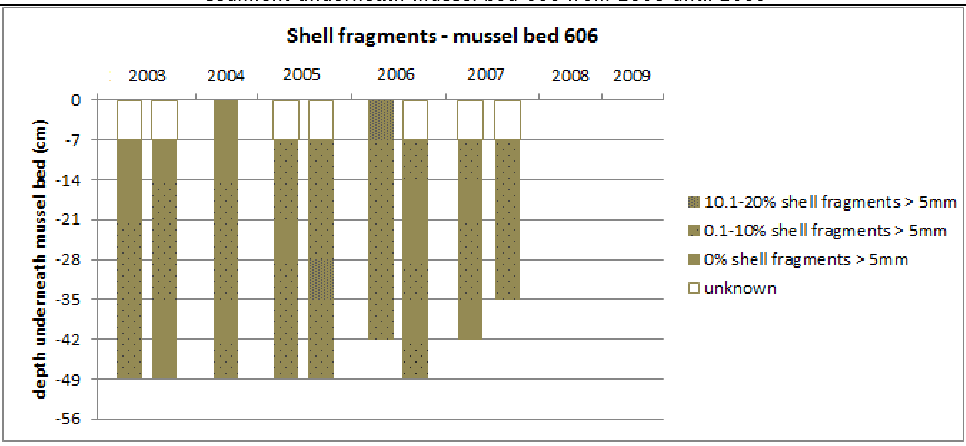


Figure 24 Presence of shell fragments (represented by particles > 5mm) underneath mussel bed 606 from 2009 until 2009

The mussel bed originates from 2001 and was visited in 2002 for the first time. At the start of the sediment measurements in 2003, the bed existed for 2 years. In that time the sediment already consisted mainly of silty sand but no deeper layers with high concentrations of shell fragments from previous years could be found. In 2004 some young blue mussels fell on the already existing mussel bed. After that the bed eroded quickly and the loss of blue mussels was not replenished by young blue mussels. Since 2008 this bed has disappeared, no live blue mussel could be found although the sediment patches were still present.

Mussel bed 607 Zuid Oost Lauwers Zuid

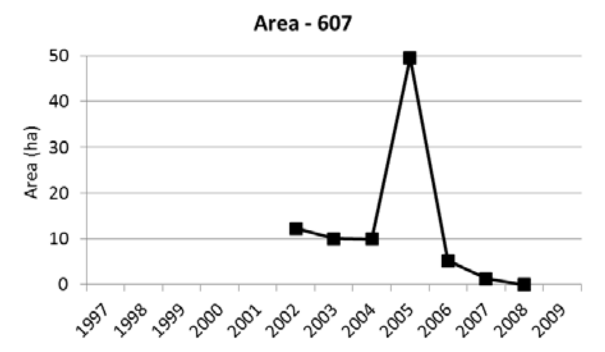


Figure 25 Area of mussel bed 607 from 1997 until 2009

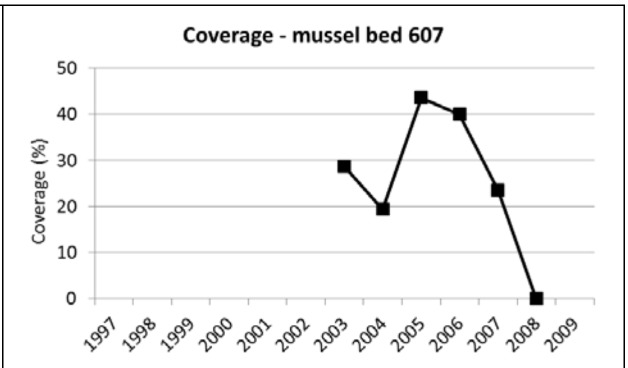


Figure 26 Coverage of mussel bed 607 from 1997 until 2009

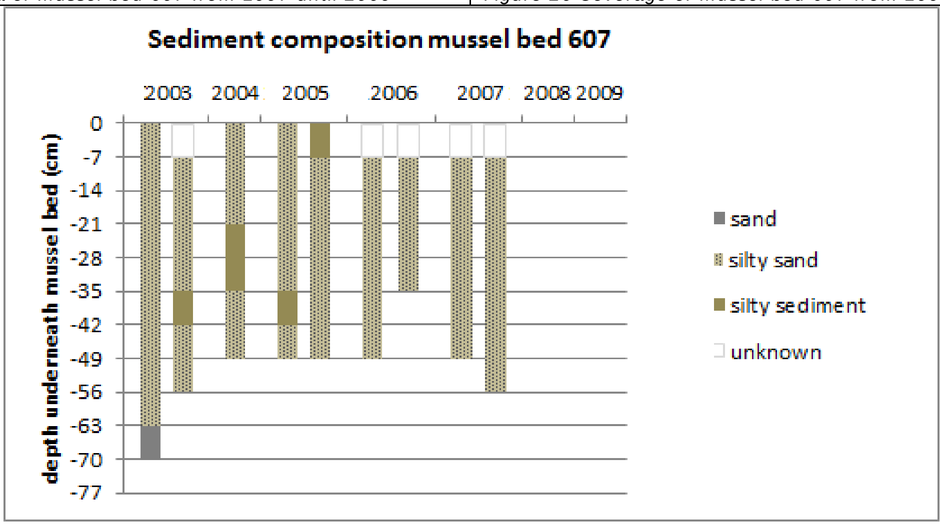


Figure 27 Sediment classification of particles < 2mm (Reineck, 1986). The classification gives insight in the siltiness of the sediment underneath mussel bed 607 from 2003 until 2009

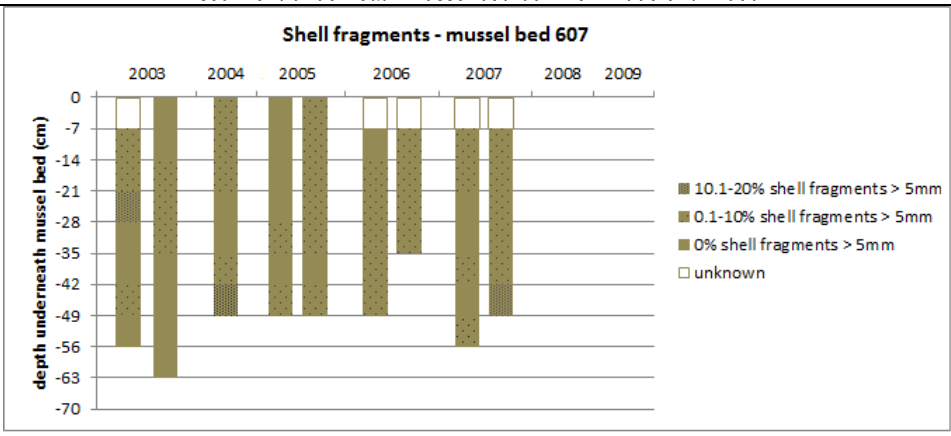


Figure 28 Presence of shell fragments (represented by particles > 5mm) underneath mussel bed 607 from 2009 until 2009

The mussel bed originates from 2000 and was visited in 2002 for the first time. At the start of the sediment measurements in 2003, the bed existed for 2 years. In that time the sediment already consisted mainly of silty sand and a deeper layer with high concentrations of shell fragments from previous years could be found. In 2005 some young blue mussels fell on the already existing mussel bed, resulting in an upper layer of silt on some locations. In 2006 the part with young blue mussel had disappeared. Since then the bed eroded quickly and the loss of blue mussels was not replenished with new spatfall. Since 2008 this bed has disappeared, no live blue mussel could be found although the sediment patches were still present.

Mussel bed 703 Rottum Wantij

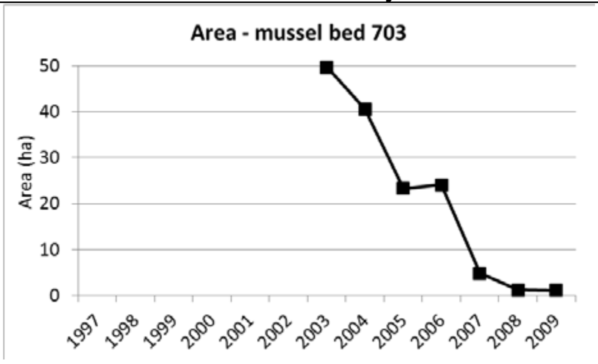


Figure 29 Area of mussel bed 703 from 1997 until 2009

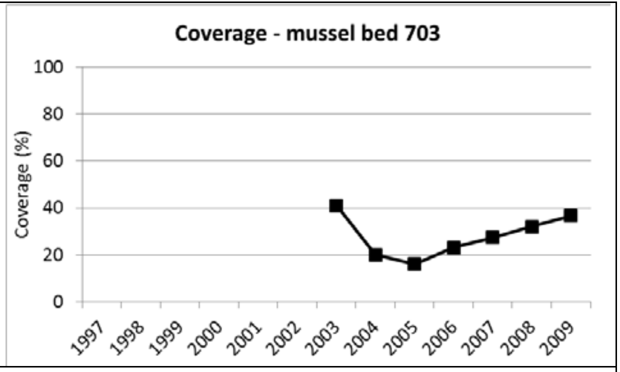


Figure 30 Coverage of mussel bed 703 from 1997 until 2009

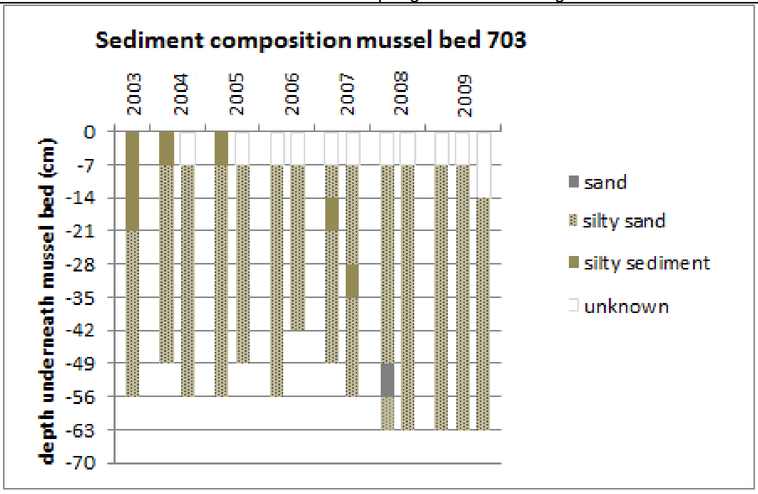


Figure 31 Sediment classification of particles < 2mm (Reineck, 1986). The classification gives insight in the siltiness of the sediment underneath mussel bed 703 from 2003 until 2009

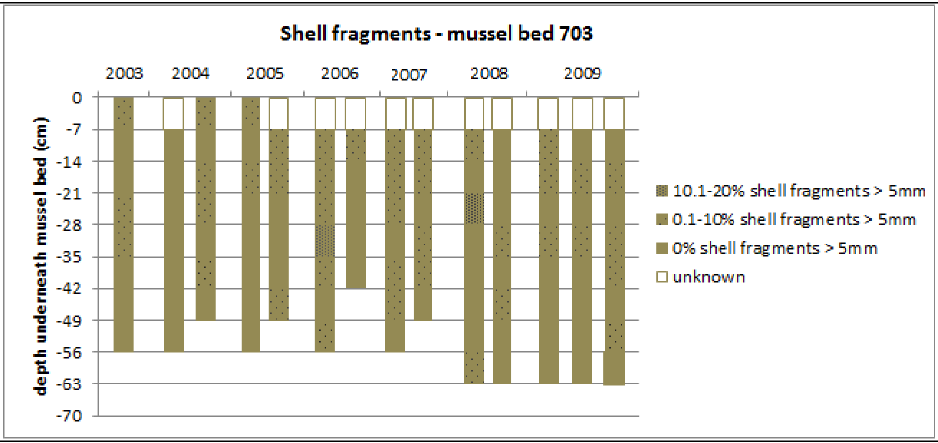


Figure 32 Presence of shell fragments (represented by particles > 5mm) underneath mussel bed 703 from 2009 until 2009

This mussel bed originates from 2001 and was visited for the first time in 2003. At that time still a thick layer of silt could be found in the upper part of the sediment. In later years the sediment became mixed with sand and shell fragments and deeper layers with high quantities of shell fragments could be found. Until 2009 no young blue mussels settled on the bed. In 2009 the mussel bed consisted only of some patches that remained from the original mussel bed. The area between these patches consists of a large silt flat with cockles, dead cockle shells, mussel shells, barnacles and some remaining blue mussels. In the summer of 2009 new spatfall covered part of this silt flat.

3.2.1.1 Summary development of sediment underneath mussel beds

It is hypothesised that a mussel bed consists of blue mussels on a thick layer of very fine silt after first settlement and that the amount of dead shell fragments and sandy particles increases over the years. This development from silt to sand with shell particles would contribute to growth in height. In this first inventory on this hypothesis it can be seen that young beds or beds with a new settlement of young blue mussels do mostly consist of thick layers of silt without shell fragments. Older beds consist mainly of silty sand with shell fragments. In those beds, deeper in the sediment layers of high quantities of shell fragments can be found. However, because yearly samples in the same bed were taken on different locations no clear development could be observed and no clear relation could be found between sediment composition or development and stability of the mussel bed. To get a better understanding of the sediment development underneath mussel beds and the relation with growth in height and stability more beds should be sampled and the samples should be taken on the same location in the bed and be combined with measurements on development in height.

3.2.2 Development of Pacific oysters

It is hypothesised that invasion of other shellfish, such as Pacific oysters, possibly add more stability to the mussel bed. Pacific Oysters stick together and form heavy clumps which are firmly anchored in the sediment. In recent years on many individual mussel beds also Pacific oysters grow, sometimes in very high densities, therefor the beds could be identified as mixed mussel-oyster bed. This structure might increase mussel bed stability. In this report a first inventory is made on the development of mussel bed areas in correlation with oyster invasion.

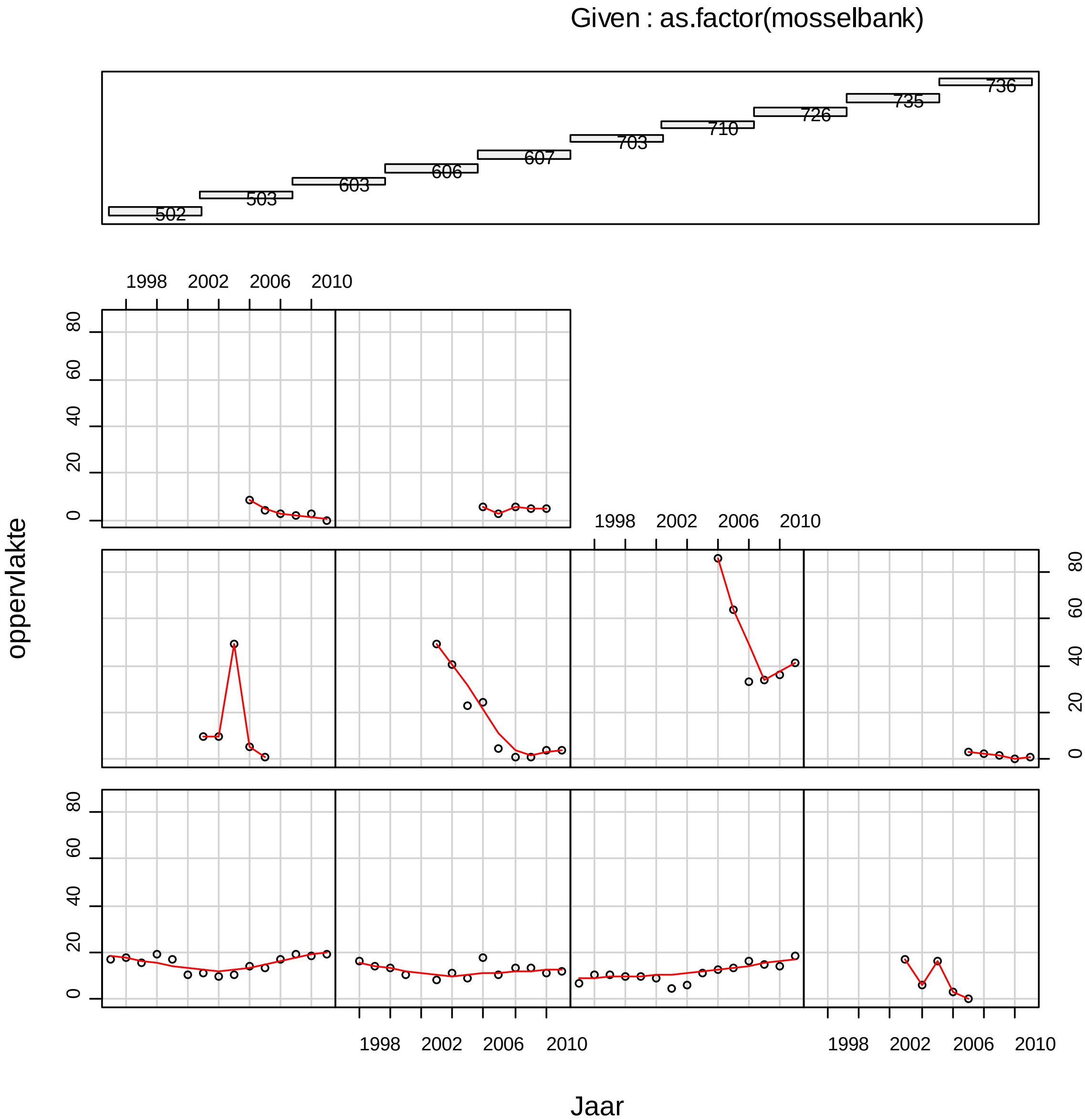


Figure 33 Development in mussel bed area of 10 individual mussel beds (502, 503, 603, 606, 607, 703, 710, 726, 735 en 736) from 1997-2010.

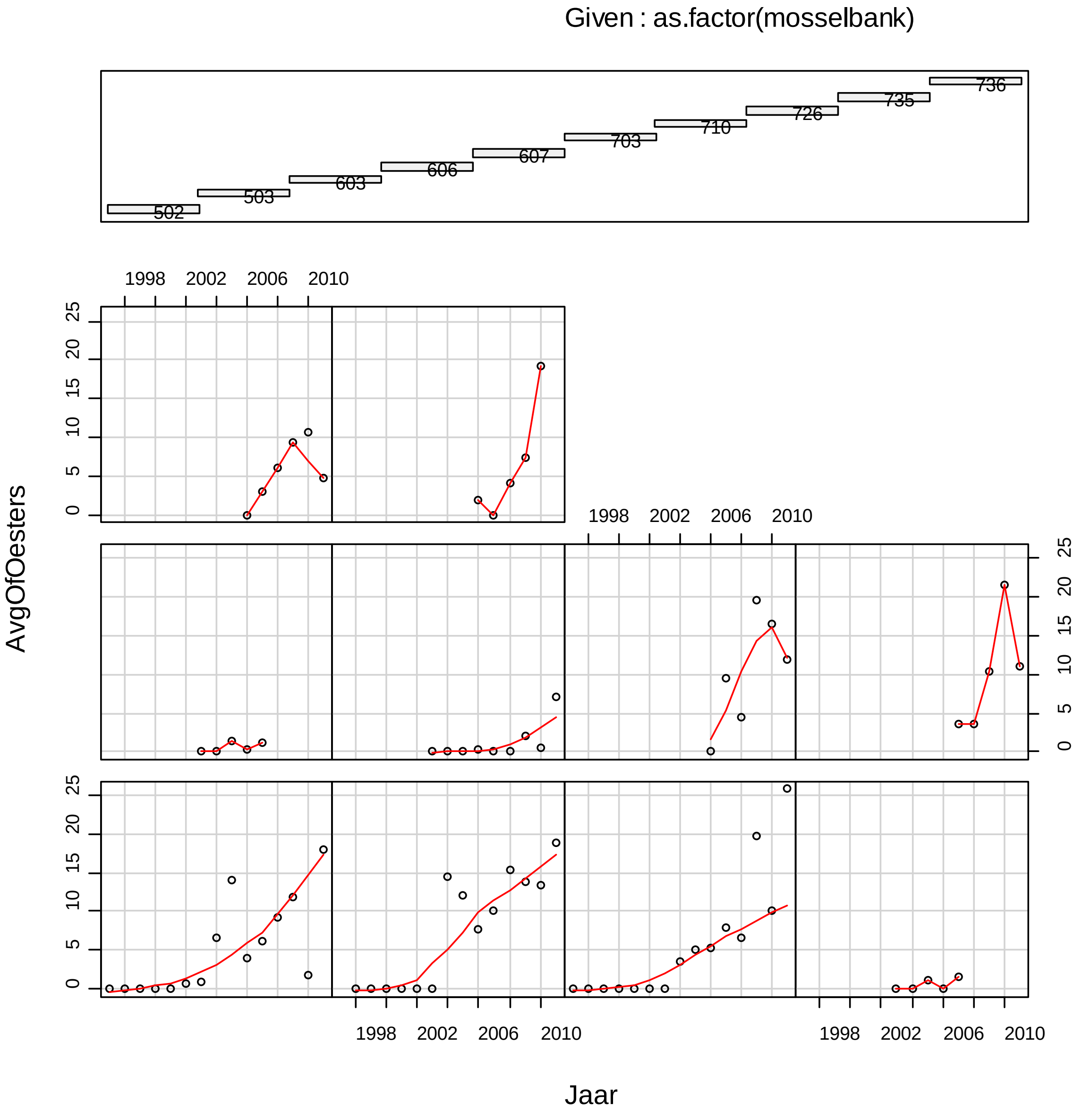


Figure 34 Oyster development in 10 individual mussel beds (502, 503, 603, 606, 607, 703, 710, 726, 735 en 736) from 1997-2010.

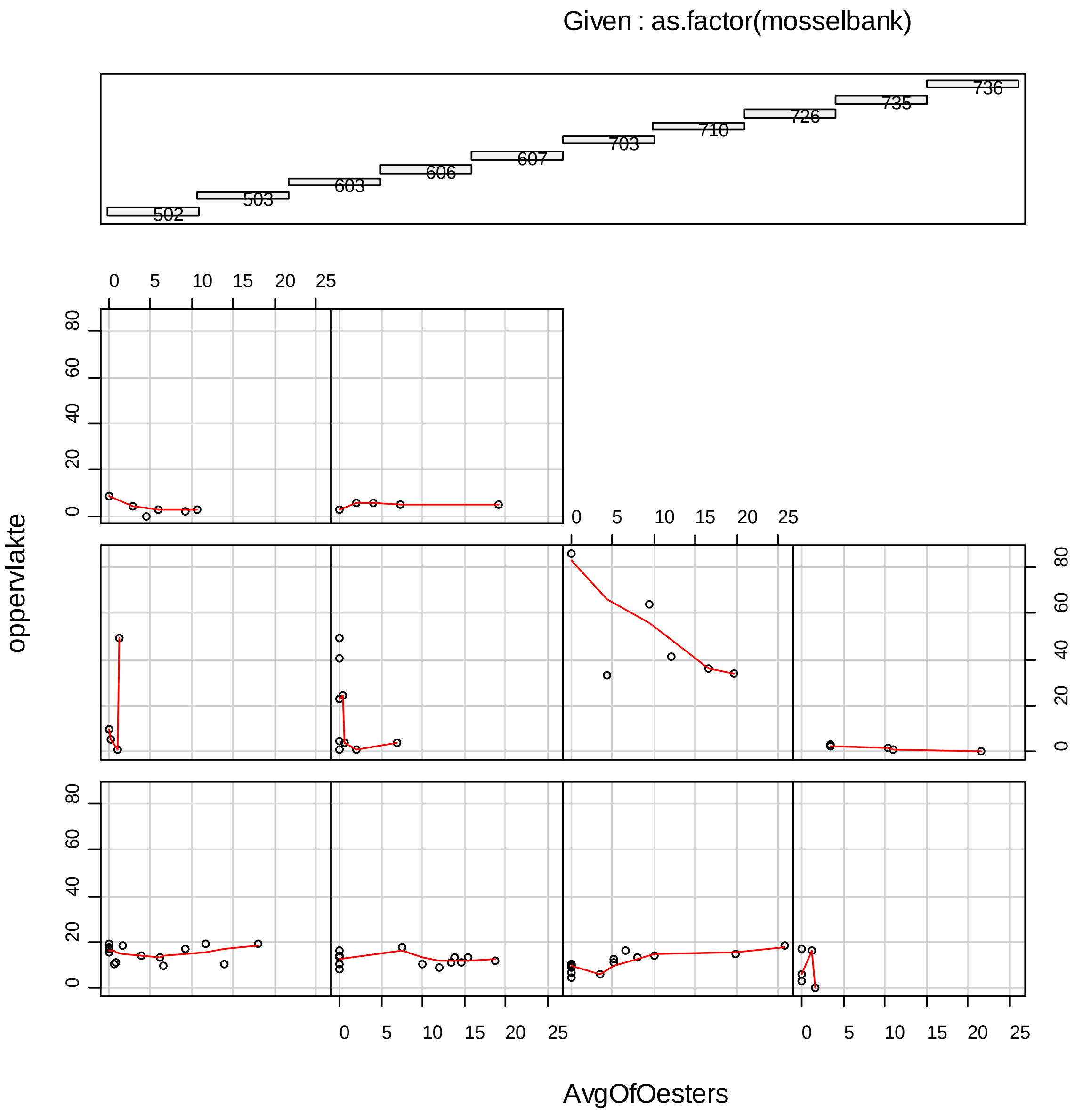


Figure 35 Correlation between the oyster development and the development in mussel bed area in 10 individual mussel beds (502, 503, 603, 606, 607, 703, 710, 726, 735 en 736) from 1997-2010.

Bed 502 Ameland Molengatplaat

This mussel bed originates from 1994 and was visited in 1995 for the first time. In 2001 oyster spat fell on the mussel bed. In 2002 this resulted in Pacific oysters of 2-3 cm, in densities of several tens of individuals/m^2. From 2008 onwards the complete mussel bed was covered with Pacific oysters but especially in the southern part they formed a reef. On the complete bed, also in the Pacific oyster reef, there are still many blue mussels in between the Pacific oysters. This mussel bed forms a stable structure which exists for already 14 years. It covered approximately 20 hectares in 2011.

Bed 503 Ameland Ballumerbocht

The mussel bed probably originates from 1994, but then eroded by strong storms. When the mussel bed was first visited in 1998 most blue mussels originated from 1996. It is known that already in 2000 many Pacific oysters could be found in the eastern part of the bed. From 2008 onward Pacific oysters can be found all over the bed, but especially in the southern part they form structures. Blue mussels can still be found in between the Pacific oysters. In the northern part blue mussels dominate and the Pacific oyster coverage is lower. The bed now forms a stable structure of at least 12 years old.

Bed 603 Schiermonnikoog Brakzand

The mussel bed originates from 1994 and was visited in 1995 for the first time. In 2004 some (young) Pacific oysters were found on the mussel bed. In the following years their number increases. From 2009 onward the middle part mainly consists of Pacific oysters, although still many blue mussels can be found in between. The mussel bed forms a stable structure of at least 14 years old and covers about 15 hectares.

Mussel bed 606 Zuid Oost Lauwers Noord

The mussel bed originates from 2000 and was visited in 2002 for the first time. Since 2008 this bed has disappeared, no live blue mussel could be found although the sediment patches were still present. Between 2003 and 2008 no Pacific oysters were found in the samples on the mussel bed.

Mussel bed 607 Zuid Oost Lauwers Zuid

The mussel bed originates from 2000 and was visited in 2002 for the first time. Since 2008 this bed has disappeared, no live blue mussel could be found although the sediment patches were still present. Between 2003 and 2008 no Pacific oysters were found in the samples on the mussel bed.

Bed 703 Rottum Wantij

This mussel bed originates from 2001 and was visited for the first time in 2003. In 2009 the mussel bed consisted only of some patches that remained from the original mussel bed. In the summer of 2009 is new spatfall covered part of the old bed. Due to this spatfall the size of the bed area increased again. In 2006 occasionally some large Pacific oysters could be found, but until now there is no significant oyster development.

Bed 710 Rottumerplaat

In 2006 this mussel bed was visited for the first time. It is not clear when the mussel bed was present for the first time, but according to Steenbergen et al. (2003) in 2003 there were already large blue mussels at this location. Probably the mussel bed originates from spatfall of 2001. The northern part which consisted of thick layers of silt, disappeared completely in 2008. When this bed was first visited in 2006 some parts of the large mussel bed were covered with Pacific oysters but the main part is still dominated by blue mussels.

Bed 726 Rottumerplaat Schild

This mussel bed was visited for the first time in 2006. It is not clear when the mussel bed was present for the first time. In 2006 already many (large) Pacific oysters were found in the south-western part. The mussel bed declined in area since then, probably as a result of storm damage. Nowadays the mussel bed is mainly covered with dead shells (blue mussel, Pacific oyster, cockle and mya), live Pacific oysters and old blue mussels can be found in between.

Bed 735 Rottumeroog

This mussel bed was visited for the first time in 2006. It is not clear when exactly it came into existence. The mussel bed yearly declines in surface. In 2006 a single oyster could be found, but their number is increasing. Nowadays blue mussels still dominate the bed.

Bed 736 Rottumeroog Oost

This mussel bed was visited for the first time in 2006. The bed probably originates from the spatfall of 2005. The southern and south-western part of the mussel bed consists of an older oyster reef. This reef probably prevents it from erosion on the relatively exposed southern side. The mussel bed consists of patches of about one meter high. The surface is stable at around 5 hectares. In 2010 the number of Pacific oysters in the inner section increased significantly, forming a more gradual transition between the two parts.

3.2.2.1 Summary Development of Pacific oysters

It is hypothesised that addition of other shellfish, such as Pacific oysters, to the mussel bed structure possibly add more stability. In 2011 a first inventory was made on this hypothesis. To study the effect of invasion of Pacific oysters on stability of mussel beds, historical data on the number of Pacific oysters in samples taken on mussel beds was correlated with the areal development of the bed. It is very clear that with the available data no correlation could be found between the number of Pacific oysters in a sample and the growth or decline in mussel bed area. Because there are many factors involved in the stability of mussel beds and because the coverage of oysters is not equaly distributed over the bed, a more elaborate study should be performed on this hypothesis. To get a better understanding the individual beds should be separated into parts with different oyster coverage. We propose to continue this analysis and expend it with an inventory on all mussel beds in the Dutch Wadden Sea. This part can be executed in cooperation with the Waddenfonds-research projects MosselWad and Waddensleutels.

4. Discussion and proposal for 2012

Stable mussel beds form conspicuous structures on tidal flats. By accumulating sediment, mussel beds grow in height and might be able to keep up with sea level rise. Stable mussel beds reduce wave action and currents. Therefore, mussel beds may help in finding sustainable solutions for coastal protection. In order to categorise the importance of mussel beds in sediment accumulation several characteristics of mussel beds are studied in the Delta programme. In 2011 a first inventory was made on the temporal development of sediment underneath mussel beds and the effect of ingrowth of Pacific oysters on the stability of the bed by means of a literature review and the analysis of historical samples taken on individual mussel beds.

4.1 Sediment accumulation

From the literature review it became clear that although some scattered information is available on sediment development and development of vertical growth, there is no data on the relation between the two. To obtain a better insight in the mechanisms of sediment accumulation, the development of vertical growth in time and the effect on stability of the mussel bed an elaborate and combined study is needed in which these factors are studied. In 2011 a first inventory was made on the analysis of historical data on sediment development in time. From several mussel beds in the Dutch Wadden Sea sediment cores, taken from 2003 onwards, have been analysed. In this first inventory it could be seen that young beds or beds with a new settlement of young blue mussels consist of thick layers of silt without shell fragments. Older beds consist of silty sand with shell fragments and deeper in the sediment layers of high quantities of shell fragments can be found. However, because yearly samples in the same bed were taken on different locations no clear development could be observed and no clear relation could be found between sediment composition or development and stability of the mussel bed. Obviously more data is needed, preferably collected on fixed locations within an individual bed. Therefore, we propose to continue this analysis in 2012 and extend it with data on the spatial development on the mussel bed and in the immediate surroundings and on the actual growth in height.

4.2 Oyster development

From the literature review it became clear that until now no scientific studies are available on the effect of Pacific oyster ingrowth on the stability of mussel bed structures. In 2011 a first inventory was made on the effect of invasion of Pacific oysters on stability of mussel beds by means of historical data. Therefore it was studied if a correlation could be made between the areal development of the bed and the development of Pacific oysters in the bed. With the available data no correlation could be found between the number of Pacific oysters in a sample and the growth or decline in mussel bed area. But it should be noted that the available data were very scattered and not collected for the purpose of this study. We propose to continue this analysis and expand it with an inventory on all mussel beds in the Dutch Wadden Sea. For this the collected data should be more spatially distributed and data on development of erosion of the bed should be more directly related to the sample point. This part can be executed in cooperation with the Waddenfonds-research projects MosselWad and Waddensleutels.

5. Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Environmental Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

Report C025/12
Project Number: 4308201070

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Dr. M.J.C. Rozemeijer
Researcher

Signature:

Date: 15th of March 2012

Approved: Drs. Jakob Asjes
Head of Department Ecology

Signature:

Date: 15th of March 2012