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# Beds of blue mussels and Pacific oysters

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## 1. Introduction



Intertidal blue mussel bed  
(Photo: Gerald Millat)

Blue mussel beds (*Mytilus edulis*) are important biogenic structures in the Wadden Sea ecosystem, serving as diverse habitat and as important food source for a number of species, especially mussel-eating birds.

Trilateral Targets for intertidal blue mussels have been adopted in 1994 and a trilateral policy and management plan for blue mussel fishery has been laid down in the Wadden Sea Plan 1997.

Strong decreases in intertidal mussel bed area in all parts of the Wadden Sea in the 1980s and 1990s led to an intense discussion about the impact of fisheries and protection measures were established. Within the entire Wadden Sea, substantial parts of the intertidal area have been permanently closed for blue mussel fisheries in order to protect mussel beds. In The Netherlands, intertidal fishery is restricted to experimental fishery on young, unstable beds outside areas

that are permanently closed. In the subtidal, unstable beds are fished in autumn, stable beds in spring. In Niedersachsen, fishery of seed mussels is allowed in the subtidal and defined parts of the intertidal, in accordance with the existing management plan, which is revised regularly. In Schleswig-Holstein, mussel fishery has not been allowed in the intertidal area nor in most subtidal parts of the national park core zone since 1997. About 50% of the Danish Wadden Sea has been closed for mussel fishery since 1992. Although mussel fishery is allowed in intertidal as well as subtidal areas, intertidal mussel beds of the Danish Wadden Sea usually remain unfished, due to a smaller tidal range.

Despite considerable efforts in mussel management, long-term observations of intertidal blue mussel beds revealed that the number and size of mature mussel beds continuously declined over the last decades in most parts of the Wadden Sea. Several factors relevant for survival of mussel beds have been discussed. At the beginning, mussel fishery was considered to be the main reason leading to a large decline of intertidal mussel beds, especially in periods of failing spatfall. As a consequence, it was proposed that the management of mussel fishery should be based on protection of sites where stable beds occur and of sites with a high potential for the development of stable beds. Recent studies, however, showed that the development of mussel stocks is not only influenced by fisheries but also affected by considerable

### Trilateral Targets for the Tidal Area (subtidal and intertidal).

- A natural dynamic situation in the Tidal Area.
- An increased area of geomorphologically and biologically undisturbed tidal flats and subtidal areas.
- An increased area of and a more natural distribution and development of natural mussel beds, *Sabellaria* reefs and *Zostera* fields.

natural factors and most probably by the proceeding climate change, e.g. the availability of seed mussels is linked to the temperature in January – March and the probability of spatfall increases with decreasing winter temperatures (Dankers and Zuidema, 1995; Strasser *et al.*, 2001a; Beukema and Dekker, 2005).

In 2007, the Interpretation Manual of European Union Habitats was updated with new definitions for the three marine habitat types listed in Annex I of the 92/43 Habitats Directive including habitat type 1170 (reefs). According to the new definition, 'bivalve mussel beds originating from dead or living animals' may be regarded as reefs, but the definition restricts this mainly to the subtidal zone as it states: 'reefs may extend from the subtidal uninterrupted into the intertidal (littoral) zone or may only occur in the subtidal zone'. Reefs have been mentioned in the standard data forms of the Wadden Sea Natura 2000 areas in Niedersachsen and Schleswig-Holstein. Although a clear definition and a protocol on how to map intertidal blue

mussel beds in the Wadden Sea based on visual methods has been available for years, this is not the case for subtidal mussel beds, where visual methods are not applicable. Therefore, member states will still have to agree on criteria and a procedure to identify and map subtidal mussel beds and how to classify them as reefs. In addition, mussel beds may also occur as parts of the habitats 1140 'mudflats' and 1110 'sandbanks' and 1160 'large shallow inlets and bays'.

In preparation for the 2010 Wadden Sea Ministerial Conference, the Trilateral Wadden Sea Plan is getting revised with mussel fishery as an important element of the plan and in conjunction with the EU Habitats and Bird Directives. The next paragraphs report on the implementation of the recommendations in the 2004 QSR, the developments of intertidal as well as subtidal mussel beds and mussel stocks since 2004, the impact of mussel fishery, and the role of bio-invasiders, especially the introduced Pacific oyster (*Crassostrea gigas*), in mussel beds.

## 2. Recommendations of the QSR 2004

In the 2004 QSR, the following recommendations were made:

1. Further research is needed to get insight into the spatfall process in general, and the cause of low recruitment of intertidal mussels and mussel beds.
2. The settlement of the introduced Pacific oysters may have a major impact on native mussel beds and their biomass in the near future. Therefore, the further spread of the Pacific oyster in and outside mussel beds as well as possible consequences to the Wadden Sea ecosystem should be subject of a detailed research and monitoring program. A common approach should be developed also aiming at development of management tools that could be used to reduce the influence of Pacific oysters on mussel beds.
3. The biotope 'intertidal blue mussel bed at stable sites' should be considered within the EU Water Framework Directive as a biological quality element for coastal waters. Additionally, because of its ecological importance, the biotope 'subtidal blue mussel bed at stable sites' should be considered as a biological quality element for water in the relevant EC Directives.
4. Substantial investigation effort is needed to document the location and extent of subtidal mussel beds in the Wadden Sea and their structure and function.
5. The management measure of protecting stable mussel beds or sites is still valid.
6. Protection of mussel beds (at stable sites) against fishery should not be restricted to the intertidal area but at least part of the subtidal beds should be protected as well.
7. To extend – if possible – the habitat model for intertidal mussel beds developed as a management tool for the Dutch Wadden Sea also to the German and Danish Wadden Sea.

Since then, progress has been made in respect of most of the recommendations, but not in all cases and not always in all regions of the Wadden Sea:

1. Mussel beds are monitored annually in The Netherlands, Niedersachsen and Schleswig-Holstein. In the Danish Wadden Sea a regular monitoring of all mussel beds in areas open for fishery is conducted every second year. The recommendations of the Trilateral Monitoring and Assessment Program (TMAP) are not always fulfilled. In The Netherlands and in Denmark, the

annual stock assessment covers both intertidal and subtidal mussel beds. In Niedersachsen and Schleswig-Holstein the main effort is concentrated on intertidal beds. In Schleswig-Holstein some information on mussel stocks and newly established spatfall areas in the subtidal is available from the vessel's blackbox data as well. Research on the important questions into the spatfall process in general, and the cause of low recruitment of intertidal mussels and subsequent survival of the mussel beds is limited. Some research on spatfall dynamics is carried out by fundamental research institutes such as NIOZ (Royal Netherlands Institute for Sea Research) in The Netherlands and AWI (Alfred Wegener Institute for Polar and Marine Research) in Schleswig-Holstein but main questions on spatfall dynamics still need to be answered.

2. The spread of the Pacific oyster has received much attention in the last years and research projects have been conducted in all parts of the Wadden Sea. A common approach to monitoring of Pacific oyster has been developed by the TMAP blue mussel group. In The Netherlands no specific monitoring for oysters is carried out, but oysters are sampled and registered in blue mussel inventories (Fey *et al.*, 2009a). In Schleswig-Holstein, Pacific oysters have been monitored since 1998 within the blue mussel monitoring. In Niedersachsen, 12 intertidal mussel beds evenly distributed in the area have been under investigation since 2003. The spread of Pacific oysters as well as their impact on intertidal mussel beds in terms of ecological functioning have been documented in two reports (Wehrmann *et al.*, 2006; Wehrmann *et al.*, 2009). In Denmark, surveys on Pacific oyster development are carried out biannually (Kristensen and Pihl, 2006, 2008). Spread of the Pacific Oyster has been further documented in a report commissioned by CWSS (Nehls and Büttger, 2007) and at a trilateral workshop in 2007.

3. An approach to include mussel beds of the Wadden Sea into quality assessments according to the EU Water Framework Directive has been made in Schleswig-Holstein (Büttger and Nehls, 2009) and this subject is in discussion in other parts of the Wadden Sea as well. In The Netherlands mussel beds are considered as a quality parameter in the habitat type 1140 (intertidal sand- and mudflats), in the subtidal (1110) and in the estuary of the Ems (1160). From Danish experiences it is regarded as a problem that beds are actually not stable but varied strongly through the years. *E.g.* the intertidal beds along

the Sædding Strand in Ho Bight in the Danish Wadden Sea have never been fished through the last 20 years, but still varied considerably both in cover and biomass. On the other hand there are also examples of beds that have survived for decades, such as between Langli and Skallingen. In Niedersachsen similar observations were made, but there, "stable sites" were recognised within beds which generally occur.

4. Monitoring of subtidal mussel beds is undertaken annually in The Netherlands on a stratified grid, but little effort is made in the other parts of the Wadden Sea. Currently, in Niedersachsen, a research project (named "Kartierung subintertidaler Habitate im Niedersächsischen Wattenmeer mittels akustischer Fernerkundung") is carried out by the Research Institute Senckenberg to detect, classify and map in detail the different types of subtidal habitats in the Wadden Sea by means of acoustical remote sensing methods. In Schleswig-Holstein, a pilot project with comparable aims on behalf of the National Park authority started in 2009. Until now, due to methodological constraints and the higher effort needed, knowledge on distribution and dynamics of subtidal mussel beds is much lower as compared to intertidal mussel beds. Within the Dutch research project PRODUS, subtidal mussel beds receive much attention, but in the other parts of the Wadden Sea the efforts to study and monitor subtidal mussel beds remain at a low level (see also QSR 2009 Thematic Report 13).

5. No changes.

6. In all parts of the Wadden Sea, substantial areas in the intertidal have been closed for shellfish fisheries. It is, however, not always well

documented whether these areas actually contain substantial parts of the mussel population. At the moment the fishery of mussels in the Danish Wadden Sea is closed due to lack of food for the birds depended of mussels (oystercatchers, eiders, gulls).

In The Netherlands, licenses are today only provided if the outcome of an appropriate assessment indicates no significant impacts on conservation targets within the Natura 2000 area. After 1 July 2008, any fishery taking place in a Natura 2000 area in Denmark has, according to the Fishery legislation, likewise to be evaluated and the ecological consequences have to be assessed before fishery can be permitted.

7. The habitat model developed in The Netherlands has so far not been extended to other parts of the Wadden Sea.

So far, the quality status description of mussel beds has been mainly focused on the area of present beds. However, due to lack of recruitment, existing beds grow older and although their areas may remain the same, the quality of the beds, in terms of cover and mussel density, decreases. Only in a limited number of beds detailed information on percentage cover, population and community structure and other relevant variables are monitored.

Moreover, over the past five years, Pacific oysters became increasingly abundant in both intertidal mussel beds and subtidal structures. Recently the debate started about when beds are still mussel beds or should be considered oyster beds. Altogether, the discussion on the quality and identity of mussel beds has started and needs to be resolved in the near future.

## 3. Development of blue mussel beds

### 3.1 Size and biomass of intertidal blue mussel / Pacific oyster beds

Overall development of mussel beds in the Wadden Sea is characterized by a marked decrease over the last decade in all areas except the Dutch Wadden Sea, where mussel beds recovered after a crash in the early 1990s (Figure 1). In all areas, Pacific oysters increased markedly and reached equal or even higher levels in biomass (live wet weight) as compared to mussels.

Most mussel beds decrease in size when storms remove areas along the wind-exposed side, although sometimes these mussels regain strongholds along the leeward site and causing the beds to grow there. The individual patch sizes also decrease resulting in a lower percentage cover, although when most of the bed disappears the remaining patches may lead to an increase of the percentage cover. Therefore the quantity (area) and quality (coverage) of the beds should not be examined independently of each other. The density per unit area also decreased.

#### The Netherlands

In their evaluation of the historical development of intertidal mussel beds, Dankers *et al.* (2003) re-estimated the area of mussel beds in the period 1960–1990. This area may have varied between 1,000 and 6,000 ha. The value of 4,120 ha for 1976

and 1978, presented in the 1999 QSR and well documented in the habitat maps for the Wadden Sea (Dijkema, 1989), lies well within this range. These mussel bed areas occurred in spite of fishery, so these estimates can be considered as minimum values of the 'natural' area. Dankers *et al.* (2003) and van Stralen (2002) described the dynamics of the Dutch intertidal mussel beds. They stated that in most years some spatfall occurs in existing beds. Losses due to storms and ice winters are often compensated by spatfall which results in the formation of new beds, but mostly in the neighborhood of or on the remainders of these.

After intensive fishery in a period with low spatfall, most intertidal mussel beds in the Dutch Wadden Sea disappeared in the period 1988–1991 (Dankers *et al.*, 1999). The oldest intertidal beds now present in The Netherlands, with a total surface of about 200 ha (Dankers *et al.*, 2003 and *unpubl. data* for recent years) are from the 1994 spatfall. The spatfalls of 1999, 2001, 2003 and 2005 are the main contributors to the present situation. Based on the ground survey and expert judgment the area of intertidal mussel beds in the spring of 2006 was estimated at about 2,600 ha (Goudswaard *et al.*, 2008; Figure 1). Since then there has been a gradual decrease (Goudswaard *et al.*, 2008; Fey *et al.*, 2008a), and the area was less than 1,500 ha in the spring of 2008 (see section 3.2).

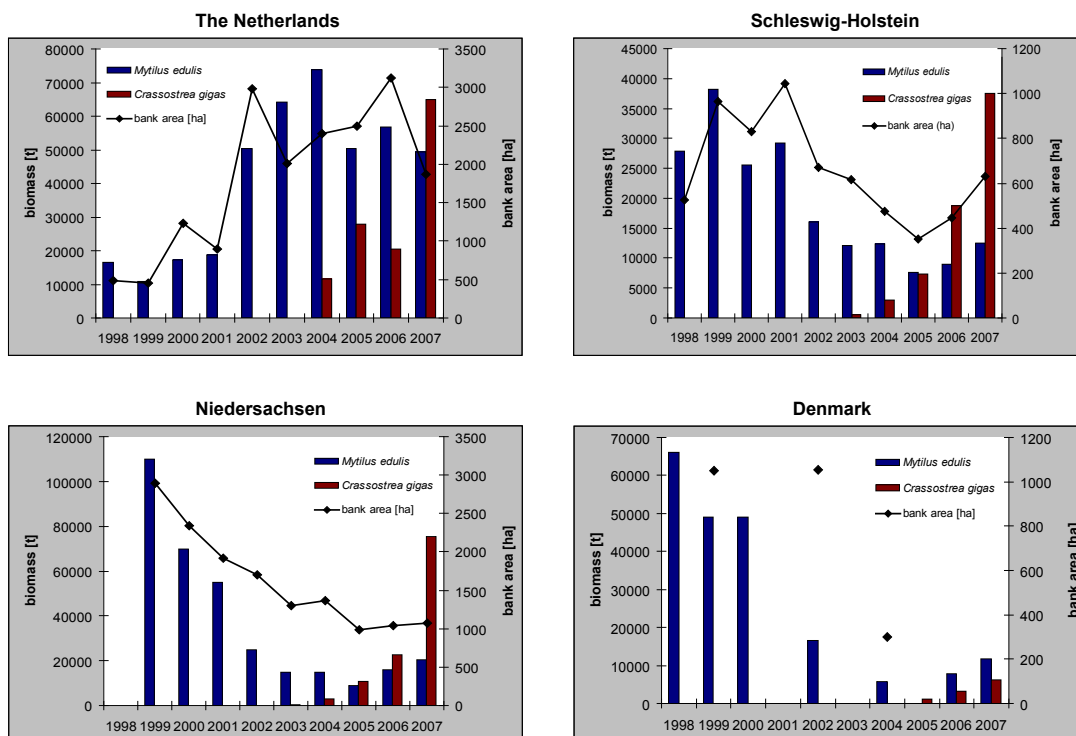


Figure 1: Development of mussel bed area and biomass of blue mussels and Pacific oysters in the Wadden Sea regions between 1998 and 2007. Biomass is given as total wet weight (Goudswaard *et al.*, 2008, Millat, Herlyn, Markert and Kristensen *pers. com.*).

Since 1991, mussel fishery has been restricted to the subtidal part of the Dutch Wadden Sea, however with two exceptions. First, fishery was allowed in the autumn of 1994 on young seed beds of the 1994 spatfall. Many of these seed beds (both fished and unfished) disappeared in early 1995 due to storms, and subsequently were heavily damaged by the severe winters of 1996 and 1997. Second, a restricted experimental fishery was carried out in 2001 on plots on beds that were considered unstable, to test the hypothesis that moderate fishery could increase the stability of young mussel beds. The experimental fishery did not show stabilization of the beds as autumn and winter storms destroyed the fished as well as unfished experimental plots (Smaal *et al.*, 2003). Therefore, it can be stated that in the Dutch Wadden Sea the mussel fishery since 1991 had no, or at the most a negligible, impact on the development of mussel beds on the intertidal flats.

Each year in spring the biomass of the mussel population in the Dutch Wadden Sea is determined by a stratified survey. The total biomass has increased from about 11,000 t fresh weight in 1999 to about 54,800 t in 2008 (Goudswaard *et al.*, 2008). In the last three years spatfall has been low, resulting in a population of older mussels (Fey *et al.*, 2008a; Goudswaard *et al.*, 2008). In this period of limited spatfall the area of mussel beds gradually decreased because natural losses are not compensated.

### Niedersachsen

Between 1950 and 1987, mussel beds covered an estimated surface area of up to 5,000 ha (Dijkema, 1989; Michaelis *et al.*, 1995). Since then mussel beds have decreased continuously. In 1994, mussel beds covered an area of only 1,300 ha. After the severe winter of 1995/96, the lowest value of 170 ha has been recorded (Michaelis *et al.*, 1995; Herlyn and Michaelis, 1996; Zens *et al.*, 1997; Herlyn and Millat, 2004) (Figure 1). In the same year a strong spatfall led to an increase of the mussel beds, but three years later the area covered by blue mussel beds started to decrease again. Since 1996, some additional spatfall occurred, leading to a mixed age structure. Over the last five years mussel bed area in Niedersachsen stabilized at 1,000 to 1,300 ha. The biomass of intertidal mussel beds showed a similar trend. In spring 1996, mussel biomass was estimated at about 1,000 tons wet weight. Following a strong spatfall in the same year, biomass increased again and reached a maximum of 110,000 tons wet weight in 1999. Up to 2005, the biomass of the mussel beds showed

a continuous decrease to 9,000 tons. Since 2005, there has been a slight increase in biomass to 20,000 tons in 2007, but surface area of the beds has shown no positive trend.

### Schleswig-Holstein

The area of mussel beds present in 1989 was re-assessed by analysis of aerial photographs and estimated at 1,500 ha. This is the highest value documented so far in this part of the Wadden Sea (Nehls, 2003; Nehls and Ruth, 2004; Stoddard, 2003). Mussel beds at that time originated mainly from the strong spatfall of 1987 which occurred after a series of three cold winters. Until today, the last good spatfall was observed after the severe winter of 1995/96 at locations that were considered to be low in hydrodynamics and mainly on the lower parts of intertidal flats and in existing mussel beds at high shore. Monitoring of blue mussel beds was resumed in 1998 (Nehls, 2003). The area covered with mussel beds in 1999 was about 1,000 ha (Figure 1). Since then, it decreased to 354 ha in 2005 which was mainly a result of storms and a lack of recruitment in this period. Percentage of cover decreased from 43% in 1998 to 26% in 2002. In the following years, the area of mussel beds increased from 445 ha in 2006 to 652 ha in 2007, which did not result from increasing blue mussel abundances but rather from successful recruitment of the Pacific oyster *Crassostrea gigas* (Nehls and Büttger, 2009).

Biomass estimates from times before the intensive fisheries of the mid 1980s are not available. After the good spatfall of 1987, 60,000 t (wet weight) were documented in 1988 and 1989. This stock decreased to 35,000 t in the early 1990s due to fisheries on 30 out of 64 beds and strong winter gales in the early 1990. Since 1992, the majority of the mussel seed fishery occurred in the subtidal and, after 1994, intertidal fishery has been abandoned. After 1996, total biomass of intertidal mussel beds increased from 32,000 t in 1998 to 40,000 t in 1999, and decreased to 8,000 t in 2005 (Figure 1). Coverage was highest in the first two years of the monitoring with 43% in 1998 and 32% in 1999. Between 2001 and 2007 coverage ranges between 19 and 27% (Nehls and Büttger, 2006, 2009).

### Denmark

For the Danish Wadden Sea, Munch-Petersen and Kristensen (1987) estimated the total area covered with mussel beds, present before the overfishing in 1984–1987, at 4,000 ha, based on aerial photographs and includes scattered mussels



('Streusiedlung') in very large areas. As these areas with scattered mussels do not meet the present criteria for mussel beds, these historic estimates should be reduced to about 2,000 ha (Kristensen, personal judgment) to allow comparison with recent data. After a period of heavy fishery, Munksgaard (1989) estimated the total area of mussel beds to be only about 500 ha in 1989 (scattered mussels were not included). In 1991, 1,100 ha were present but in 1996 the area decreased again to only 600 ha (Kristensen, 1997). In 1999, the area had increased again to 1,000 ha (Kristensen and Pihl, 2003) (Figure 1). The areas with mussels varied considerably since the mid 1980s but never exceeded 2,000 ha. In the Juvre Dyb, Mandø and Knude Dyb areas, beds never returned after their removal by fisheries. In the Ho Bight area (partly closed for fishery), almost 70% of the original beds returned by an autumn settlement immediately after the breakdown in 1989. This situation remained stable in the years after 1999. Some intertidal beds disappeared and some new beds appeared. In 2002, 650-900 ha of mussel beds were present (Kristensen and Pihl, 2003). So, the area covered with mussel beds as well as the biomass has been variable over the years (Kristensen, 1997; Kristensen and Pihl, 2003).

### 3.2 Distribution and age composition of intertidal blue mussel beds in the Wadden Sea since 1999

Overall distribution of mussel beds in the Wadden Sea changed over the last decade. Mussel bed area in the northern half of the Wadden Sea strongly decreased whereas it was more stable in the eastern Dutch Wadden Sea and the western part of Niedersachsen (Figure 2).

#### The Netherlands

The age structure of the mussels on the mussel beds varied considerably (van Stralen, 2002; Steenbergen, 2003; Goudswaard *et al.*, 2008). Marked spatfall events occurred about every 2-4 years, and there are indications of large variations in sizes of the beds (Dankers *et al.*, 2004). Because of this irregular occurrence, age composition also varies substantially between years. In years after a considerable spatfall, small mussels may dominate the population, but a few years later different cohorts shape the population because, even in poor years, some spatfalls occurs in existing beds.

Survey data indicate that in the Dutch part of the Wadden Sea several major spatfall events oc-

Figure 2: Distribution of intertidal blue mussel beds in the Wadden Sea in the period 1999-2007.

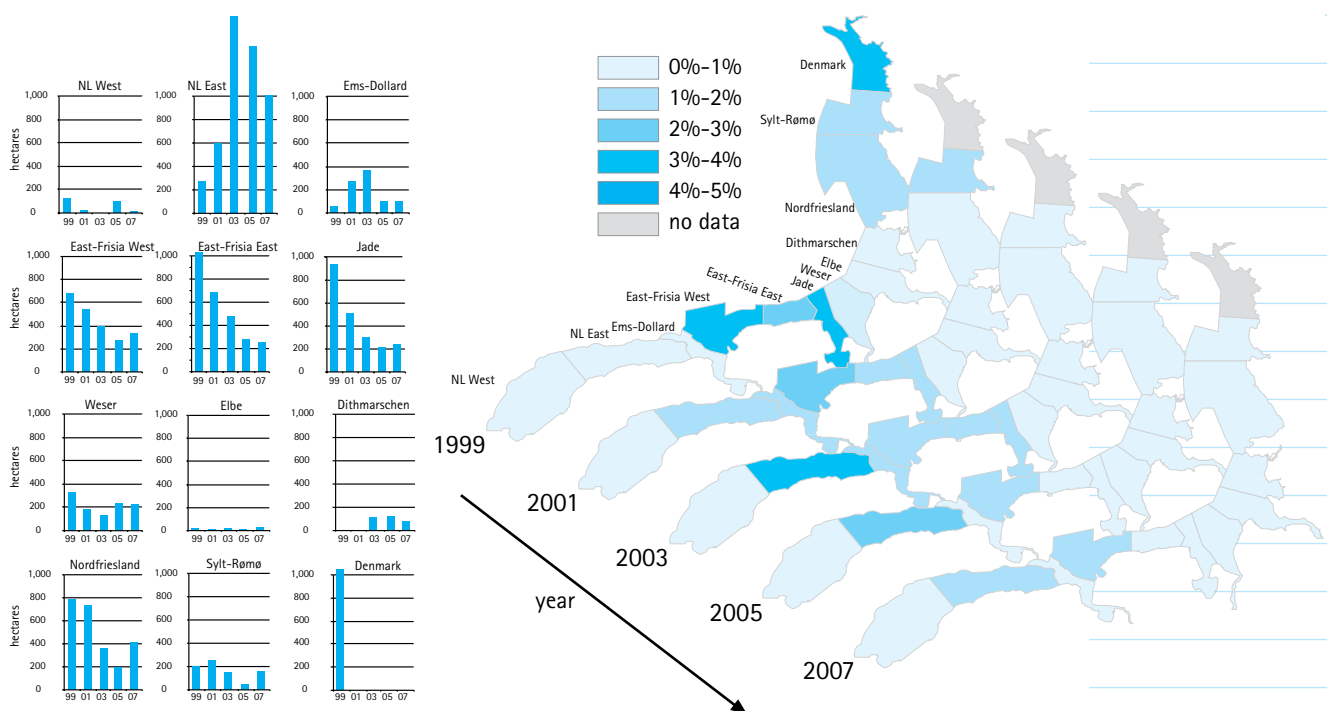
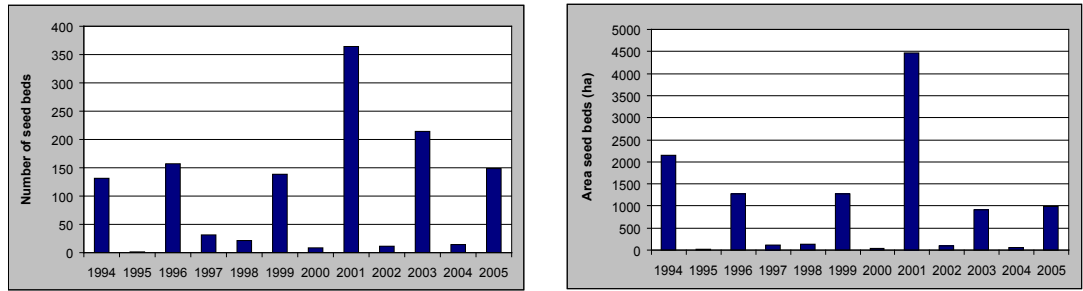


Figure 3: Number (left) and area (right) of intertidal seed mussel beds in The Netherlands from 1994 to 2005.



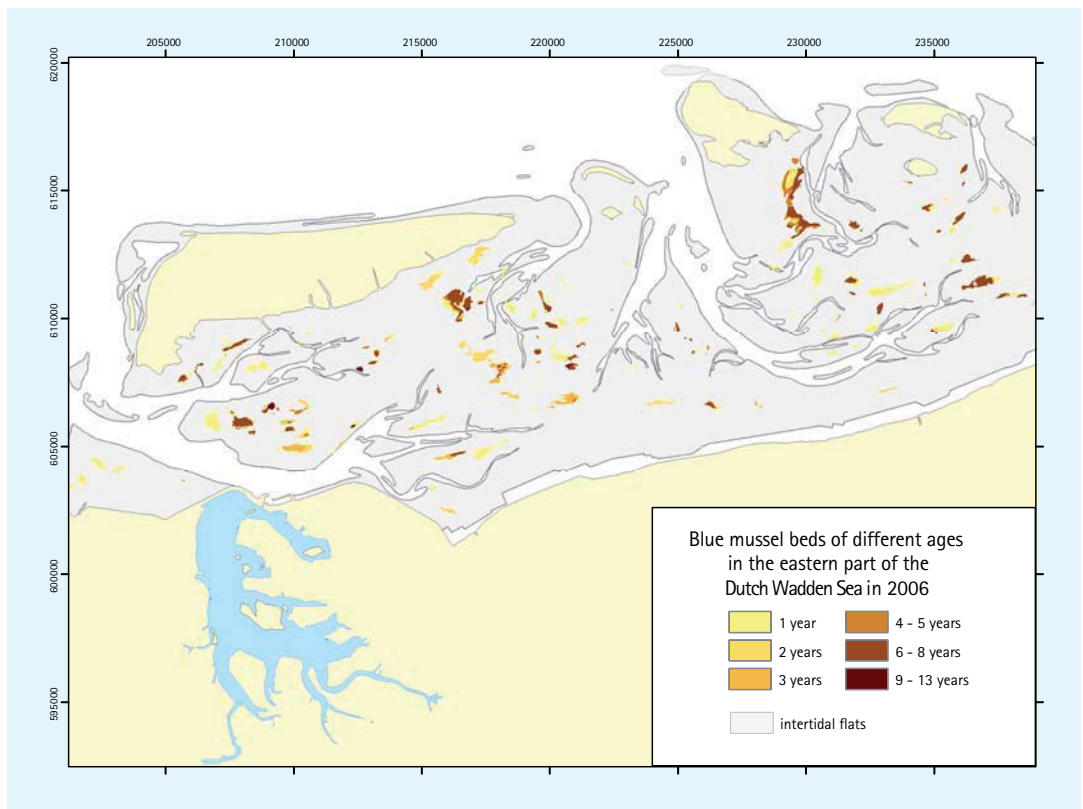
curred over the last 20 years. Good to reasonable years, with spatfall either on existing beds or resulting in new seedbeds, are 1984, 1985, 1987, 1994, 1996, 1999, 2001, 2003 and 2005. Figure 3 gives the number as well as the area of seed mussel beds in the Dutch Wadden Sea. In years of good spatfall, between 100 and 150 new beds establish and an area of 1000 ha new seed beds is quite common.

Since 1995, all beds have been mapped each spring. Several beds have reached an age of more than 10 years. Maps of beds or parts of beds of different ages are available at IMARES. An example of a small area is given in Figure 4.

### Niedersachsen

Until the end of the 1990s, the age structure of the mussel beds in Niedersachsen was dominated by blue mussels from the spatfall in 1996, which reached densities above 75,000 ind./m<sup>2</sup> in the settling stage (Herlyn *et al.*, submitted). As a consequence of decreasing numbers of older mussels and local spatfalls, the population structure mixed in age over the course of the years. Especially smaller mussels settle in the manifold system of gaps within mixed blue mussel/oyster beds providing shelter e.g. from predation (Markert *et al.*, 2009).

Figure 4: Mussel beds of different ages in the intertidal area south of the Dutch islands of Schiermonnikoog and Rottum.



### Schleswig-Holstein

Mussel beds have been recorded in about 200 locations so far. They are not evenly distributed within the Wadden Sea of Schleswig-Holstein but are high in numbers in the Lister Deep, between the islands of Amrum and Föhr and east of the island of Pellworm. In some areas where mussel beds were abundant in former years, such as the Hörnum Deep and the area east of the island of Föhr, only a few mussel beds are currently present. Since 2000, only few newly established blue mussel beds have been recorded in the area between Eiderstedt and the Danish border because of insufficient recruitment success (Figure 5). The difference with the situation in the Dutch part (Figure 3) is striking.

The age structure of the mussels indicated in the late 1990s that mussel beds were dominated by the 1996 recruitment event that followed upon the severe winter in 1995/96. In the following years spatfall varied regionally. Mean densities of new settlers in the mussel beds in September averaged 500 ind./m<sup>2</sup> in the Lister Deep and 1,200 ind./m<sup>2</sup> in Norderhever and Rummelloch. A strong spatfall leading to the colonization of new beds reaches 10,000 to 50,000 ind./m<sup>2</sup>. In all years some spatfall occurred in spring, but it was usually much weaker than in late summer, and reached locally up to 6,000 ind./m<sup>2</sup>. In most years, spatfall did not result in new beds and was insufficient to compensate for losses in existing beds (Nehls and Büttger, 2006).

### Denmark

After the breakdown of the mussel stock in the Danish Wadden Sea in 1988, mussel beds rapidly recovered in many areas - as soon as the following year. In 1989 densities up to 100,000 ind./m<sup>2</sup> (shell length < 5 mm) have been determined for intertidal mussel beds in Ho Bight (Munch-Petersen and Kristensen, 2002). In 2002, the abundance on patches still covered by mussels reached 2,000 ind./m<sup>2</sup> (shell length ~ 55 mm) (Munch-Petersen and Kristensen, 2002). On these patches the biomass must have increased from around 5 kg/m<sup>2</sup> to 30-50 kg/m<sup>2</sup>. In recent years, mussel beds in the intertidal in Ho Bight recovered and reached a stock size comparable to 1989 (Kristensen and Phil, 2008).

### 3.3 Subtidal mussel beds

Ecological conditions differ greatly between subtidal and intertidal areas of the Wadden Sea, leading to different developments and structures of mussel beds and associated communities. Subtidal mus-

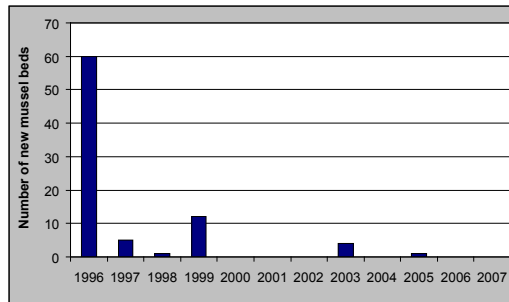


Figure 5:  
Number of new or re-established mussel beds in Schleswig-Holstein since 1996.

sels reach larger sizes and higher meat contents as compared to intertidal mussels. Knowledge on distribution, structure and ecology of natural subtidal mussel beds is limited in most parts of the Wadden Sea and little is known about productivity per area. It is also not clear to what extent subtidal mussel stocks could be classified according to the TMAP definition for intertidal mussel beds. Comparative field investigations of intertidal and adjacent shallow subtidal mussel beds near the island of Sylt in the northern Wadden Sea revealed substantial differences in biogenic mussel bed structure, species interactions and associated organisms. In this area, total number and distribution of associated species differ between intertidal and subtidal mussel beds. Some species occur in both tidal zones, but many are restricted to either intertidal or subtidal sites and especially subtidal mussel beds harbor a distinct and more diverse community of associated organisms (Saier, 2002; Buschbaum and Saier, 2003). Subtidal mussel beds are often more overgrown by epifauna, especially barnacles and slipper limpets, but little is known about endofauna of subtidal mussel beds. Structural differences include lower densities of mussels on subtidal than on intertidal beds (Saier, 2001, 2002; Buschbaum and Saier, 2001). Additionally, mussel individuals on intertidal beds are smaller. Therefore, in the northern Wadden Sea intertidal and subtidal mussel beds are ecologically different (Saier, 2002; Buschbaum and Saier, 2003). It is not clear, whether these results can be generally applied to other areas as well. However, it is also known from other parts of the Wadden Sea that natural subtidal mussel beds may have their own characteristic and species-rich community (Buhs and Reise, 1997 and references therein; Westphalen, 2006).

In former times, blue mussels were collected and fished from wild intertidal and subtidal mussel beds. This strategy changed with increasing mussel demand in the middle of the last century to subtidal bottom cultures in the Dutch and German

parts of the Wadden Sea (Dankers and Zuidema, 1995; Seaman and Ruth, 1997). The bottleneck for a successful mussel culture is the availability of juvenile seed mussels which are predominantly fished from the subtidal zone. The resulting high fishery pressure causes a number of possible impacts such as changes in seabed topography and disturbance of non-target organisms (Kaiser and Spencer, 1996). Additionally, fishery for seed mussels may affect the establishment of natural perennial subtidal mussel beds and at present these can be hardly found. However, the subtidal zone may become of increasing importance for mussels and may provide a refuge because intertidal beds are heavily overgrown with the Pacific oyster *Crassostrea gigas* (see section 4) and have partly shifted to oyster beds with changes in the associated species community and ecological function (Kochmann *et al.*, 2008; Markert *et al.*, 2009). Additionally, well established subtidal mussel beds may provide a nursery ground for juvenile mussels. Field experiments have shown that mussel recruitment on well established highly structured subtidal beds is about 20 times higher than on short living and less diverse culture lots (Buschbaum, unpubl. data). Thus, subtidal mussel beds are of high ecological value and more consideration should be concentrated on this comparatively less investigated but important habitat.

### 3.3.1 Status and exploitation of subtidal mussel beds

Annual landings of blue mussels in the Wadden Sea show a long-term decrease which is mainly attributed to the development in The Netherlands

(see QSR 2009 Thematic Report 3.5 Fishery). In the other parts, landings are rather variable, but low over the last years.

## The Netherlands

### Status

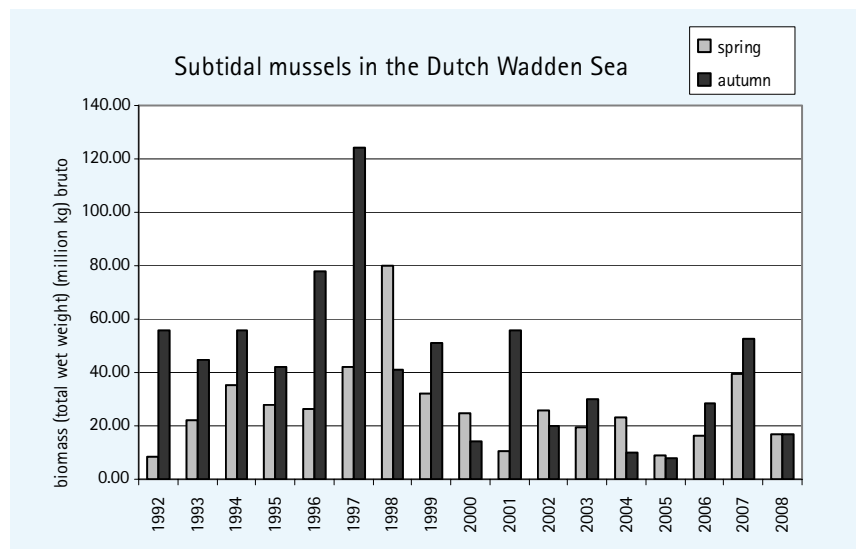
The location of subtidal mussel beds and their biomass has been monitored annually since 1992, in order to regulate fishery for seed mussels needed by mussel farmers to stock their culture lots. In The Netherlands, subtidal mussel beds mainly occur in the westernmost part of the Wadden Sea, in an area of about 500 km<sup>2</sup>, in the vicinity of the 'Afsluitdijk'. The biomass is presented in Figure 6. Figure 7 shows the area where subtidal young mussel beds occurred in the period 1997–2007. This area, with large subtidal mussel beds interspaced with the channels of the Marsdiep tidal basin and some relatively low intertidal flats that hardly emerge during low tide, is influenced by release of fresh water via sluices in the 'Afsluitdijk', causing more or less brackish conditions with salinity usually between 15 and 25 PSU.

### Mussel fishery

All natural subtidal mussel beds in the western Dutch Wadden Sea are heavily exploited by mussel farmers, collecting young or half-grown mussels ('seed mussels') to stock their culture lots. Due to fluctuating recruitment success the total biomass is highly variable, ranging from less than 10,000 to about 80,000 t fresh weight during the period 1992–2008 (Figure 6).

New spatfall occurs fairly often, leading to a moderate to good recruitment in some years, but there are also many years with almost failing

Figure 6:  
Biomass (total wet weight) of subtidal mussels in the Dutch Wadden Sea in spring and autumn from 1992–2007 (adjusted to Fey *et al.*, 2008b).



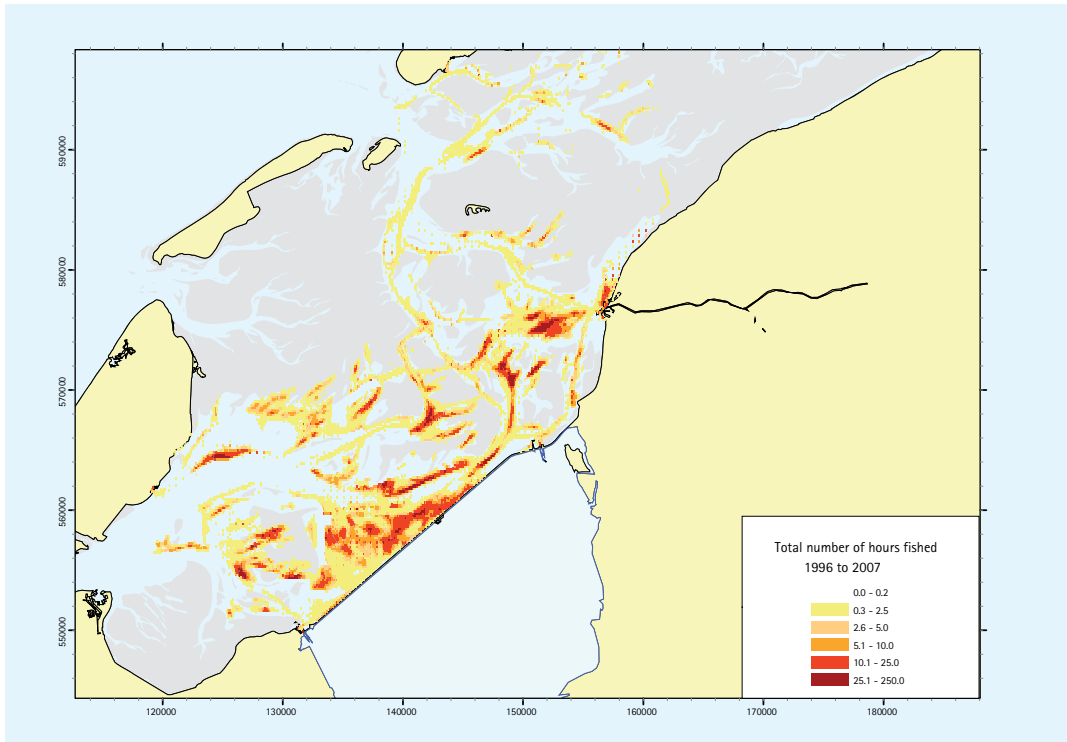


Figure 7: Subtidal seed mussel beds in the Dutch Western Wadden Sea depicted by fishing intensity.

spatfall. After 1990, however, recruitment appears to be less frequent than before, leading to lower biomass values than in the period 1970-1990 (Figure 8) (Brinkman and Smaal, 2003; Ens *et al.*, 2004).

There is no knowledge about the potential, age structure or biocoenosis of subtidal mussel beds in absence of fishery. A proposal has been made in the new Dutch fishery policy (2004) to establish some areas in which the development of undisturbed subtidal mussel beds can be studied, and the first bed of 100 ha has been protected since 2009 (see QSR Thematic Report 3.5 'Fishery').

## Niedersachsen

### Status

In Niedersachsen natural subtidal mussel beds have been recorded on every occasion within the last decades, but data about area and biomass are missing. In recent years, subtidal mussel beds between Borkum and Cuxhaven could not be recorded any longer, except for some young mussel aggregations.

### Mussel fishery

Due to the increased occurrence of the Pacific oyster, seed mussel fishery in the intertidal be-

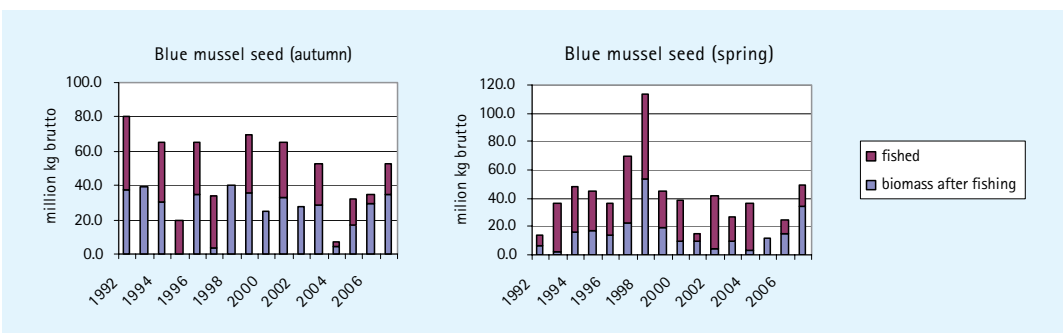


Figure 8: Biomass and fished mussels in autumn (left) and spring (right).

came less attractive in recent years, in some parts mussel fishery was even not practicable any longer. Recently, the deficiency of intertidal seed mussels is substituted mainly by seed mussel fishery of subtidal beds (Anonymus 2006, 2007). Furthermore, the enhanced use of seed collectors in the form of long-line cultures was developed in the Jade.

### Schleswig-Holstein

#### Status

Subtidal mussel stocks were detected during partial annual surveys in 13 locations of the North Frisian Wadden Sea (Nehls and Büttger, 2006). Although no data on distribution and biomass could be gathered, the results indicate stable subtidal sites with regular recruitment in some locations. About a third of the subtidal area where spatfall can be expected has been closed for seed fishery since 1997. Actually, there is relatively little information about the subtidal stocks in the area closed for the seed fishery.

In 2003, some successful spatfall occurred in the area south of Sylt, south of the Hallig Langeness and in the area near Büsum. In 2004, spatfall has been observed only at one location near Büsum, but the mussels remained very small and died off very soon. In 2005, spatfall was again restricted to two small locations near Büsum. In 2006, 2007 and 2008, no spatfall at all has been observed in the Wadden Sea area of Schleswig-Holstein.

#### Mussel fishery

In Schleswig-Holstein, mussel seed fishing of new spatfall starts as early as possible, normally in July or early August at a mean mussel length of about 5 mm. Seed fishing is continued until late October/November when the mussels have reached mean length of about 35 mm. Quantities are not restricted, and the capacity of the fleet is high enough to reduce all existing stocks in the areas that are allowed to fish down to below 0.1 to 0.05 kg/m<sup>2</sup> until the next July. The companies start a common search for suitable mussel stocks in July, and are able to detect any reasonable stocks within the area they are allowed to fish for spat, e.g. the subtidal area outside the core zone of the national park. They are allowed to fish spat mussels within four small areas within the core area too, and may apply for permits for additional areas. Under this agreement they also make some effort to detect stocks in the entire core zone too. From 2004 onwards, only a few areas with reasonable

stocks have been detected; since 2006 no fishable spatfall has been observed. Consequently there is pretty good evidence that no reasonable subtidal mussel stocks exist in the Schleswig-Holstein Wadden Sea at present.

### Denmark

#### Status

Subtidal mussel beds in the Danish Wadden Sea are small compared to beds found in the intertidal. The area is estimated at about 200 ha since the survey program began in 1986 (Munch-Petersen and Kristensen, 1987, 2002). The main subtidal beds are situated in the Ho Bugt area. Some subtidal beds have disappeared and new ones have appeared. Subtidal beds are also found in Knude Deep and in Lister Deep. Those were formerly regularly exploited by fishery.

A nature conservation project started in 2002 to study whether transplantation of seed mussels to Jørgens Lo and Ribe Stream could contribute to re-establishment of mussel beds in this area. The results of the experiment were disappointing. Due to strong currents, the transplanted mussels of around 116 t were carried away from the subtidal to the intertidal area. However, they did not establish a new spawning stock as planned and expected.

#### Mussel fishery

There are no culture lots in Denmark and no fishing for seed mussels takes place. Export of seed mussels to The Netherlands or Schleswig-Holstein is prohibited.

The subtidal beds in Ho Bight are regularly fished, restricted by a quota set by the government. Since 1989, only limited fishing has taken place on subtidal mussel beds in the Lister Deep area.

No fishery has taken place in the last four years because the biomass of blue mussels present in the Danish Wadden Sea has been below the food level demands of the most important mussel-eating bird species (oystercatcher, eider and herring gull). A new estimation of the food demand for these species may postpone the possibilities of mussel fisheries for several more years and even endanger mussel fisheries in the Danish Wadden Sea. In 2009 it has been decided by the authorities responsible for the Danish Wadden Sea, to allocate 37,000 t (wet weight) of mussels in the future to the three bird species mentioned.

### 3.3.2 Culture lots

Culturing takes place in all areas of the Wadden Sea except for Denmark, which only allows quotas for direct landings from natural beds. Mussel beds on culture lots represent a man-made type of subtidal mussel bed with more disturbances (relaying, removal of seastars and algae) and therefore with a less diverse associated fauna than natural mussel beds.

#### The Netherlands

Currently, the total available area for culturing amounts about 7,600 ha, of which about 3,300 ha is stocked with mussels. The production at the culture lots in the Dutch Wadden Sea has tended to decrease since 1990 due to shortage of seed mussels.

#### Niedersachsen

Most culture lots in Niedersachsen are situated between the islands of Borkum, Juist and the mainland, and along the east side of the Jade and in the Jadebusen. Their total surface is about 1,300 ha. Fishing for seed mussels takes place in both intertidal and subtidal areas. Occasionally, seed mussels have been imported from Great Britain (Anonymus, 2005).

#### Schleswig-Holstein

Most of the culture lots in Schleswig-Holstein are situated in the northern part of the area, between Pellworm and the Danish border. The area of all culture lots in Schleswig-Holstein was reduced from an area of about 3,000 ha to a maximum of 2,000 ha at the end of 2006. Only two-third of the total surface can be used simultaneously. The remaining area is needed for replacing mussels from exposed to sheltered lots and vice versa. The landings of blue mussels in Schleswig-Holstein in 1985–2007 varied considerably. As the market has not been saturated since 1989, this variation is an expression of the availability of seed mussels in the preceding years.

#### Denmark

There are no culture lots in Denmark. All Danish blue mussels for human consumption are harvested from natural mussel beds in the subtidal area which are open for fishery.

## 4. Invasion of the Pacific oyster

### 4.1 Status of the Pacific oyster

Overfishing of the native European flat oyster beds (*Ostrea edulis*) at the end of the 19th Century resulted in a dramatic decline in the native oyster populations of the Wadden Sea. In the North Sea region, imports of *Crassostrea gigas* started in 1964 to The Netherlands, England, and France, later followed by Germany. The cultivation of the Pacific oyster *C. gigas* turned out to be successful. In most regions, the Pacific oysters did not remain restricted to their culture lots but reproduced and also dispersed in the Wadden Sea (Figure 9). The success of natural recruitment and the rate of spread are different in specific regions and seem to depend on abiotic factors. Total biomass in the Wadden Sea was calculated at 190,000 t total wet weight (TWW) in 2007. The most recent regional figures are as follows: The Netherlands: 65,000 t, Niedersachsen: 75,550 t, Schleswig-Holstein: 43,606 t, Denmark: 6,264 t. However, due to sampling difficulties the accuracy of these figures should be regarded with care.

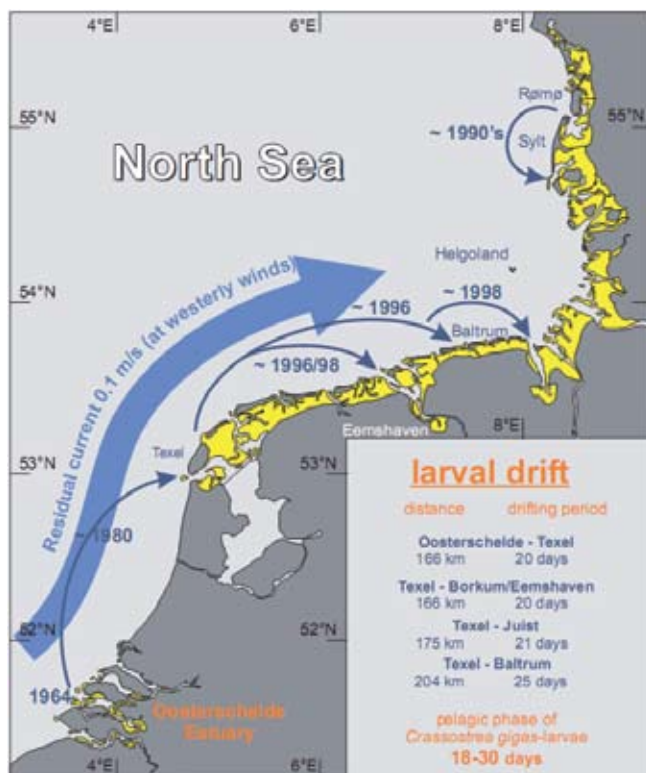
Today, the Pacific oyster is found in all parts of the Wadden Sea, leading to the most obvious change in the habitat structure of mussel beds in the Wadden Sea. Oyster larvae settle on any kind of hard substrate (Fey *et al.*, 2009a), mainly as epibionts on intertidal mussel beds. A posi-

tive feedback in settlement (Troost *et al.*, 2004; Diederich, 2005; Wehrmann *et al.*, 2006) leads to cluster formation while areas with high densities are characterized by rigid and stable bioconstructions (Rabe, 2008; Wehrmann *et al.*, 2009).

Due to its high growth rate and recruitment success, accelerated by high summer temperatures and missing natural predators, the Pacific oyster is considered to be a potential risk to the mussel beds of the Wadden Sea. Being a suspension feeding organism, *C. gigas* competes with the native blue mussel for food as well as for space. Blue mussels have higher filtration rates than equal sized oysters (May, 2006). However, total amount of filtration capacity depends on biomass. As an ecosystem engineer, oysters are promoting complex and biodiverse communities, replacing and enhancing the ecological function of intertidal blue mussel beds in the Wadden Sea (Markert *et al.*, 2009).

Contrary to the native blue mussel, this species seems to be largely restricted to the intertidal during the first years of development (Nehls and Büttger, 2007; Kristensen and Pihl, 2008). In the Netherlands oysters occurred in large densities in the subtidal of the Eastern Scheldt, and recently also in the Wadden Sea there is a strong increase in the subtidal (Lang and Buschbaum 2009). In

Figure 9: Pacific oysters in the Wadden Sea: Potential drift ways and year of invasion of *Crassostrea gigas* larvae from the known culture plots and wild populations of the Oosterschelde estuary and Texel into the backbarrier area of the East Frisian Islands, southern North Sea (Wehrmann *et al.*, 2000).





Niedersachsen, Pacific oysters have been reported in the subtidal at southern Randzel and in the Jade (Wehrmann, *unpubl. data*). In Schleswig-Holstein subtidal stocks are known from the Lister basin. Subtidal surveys (dredge hauls) between 2005 and 2007 in different channels outside the List basin detected only a few individuals in the subtidal, which might be transferred there by currents or storm events (Nehls and Büttger, 2007). There is evidence that in the Hörnum Deep near the island of Sylt, a strong spatfall from 2006 formed out large subtidal stocks of *C. gigas* (Ruth, *unpubl. data*). Reise (*pers. com.*) searched the subtidal parts of the Lister Deep for Pacific oysters in 2006 and reported a mean density of about two oysters per 100 m<sup>2</sup>. In Denmark, subtidal Pacific oysters are reported in the Limfjorden (Kristensen *unpubl. data*).

### The Netherlands

In 1983, wild grown Pacific oysters were first recorded near the island of Texel (Bruins, 1983), resulting from direct releases of oysters imported from the Oosterschelde (Tydeman, 2008). Since 2000, *C. gigas* is found in all parts of the Dutch Wadden Sea, although in most places in small numbers. After the rapid spread until 2004 the mean densities on several places (transect of Oudeschild, oyster bed Zeeburg, mussel bed near Ameland) seemed to stabilize, but densities still increased on a mussel bed near Ameland in 2006 (Fey *et al.*, 2009a). The maximum density reported by Fey *et al.* (2007) in the Dutch Wadden Sea was found on the oyster bed near Zeeburg (Texel) with more than 500 ind./m<sup>2</sup> in 2003. The area with a clear dominance of Pacific oysters in the Dutch Wadden Sea covered about 430 ha in 2005 and slightly decreased again in 2006. Areas with a

mixed community of Pacific oysters and blue mussels increased since 2004, which might be a result from mussel spatfall. Scattered oysters were found in another 250 ha in 2005 and this area increased in 2006 up to nearly 400 ha indicating that Pacific oysters start to populate new areas.

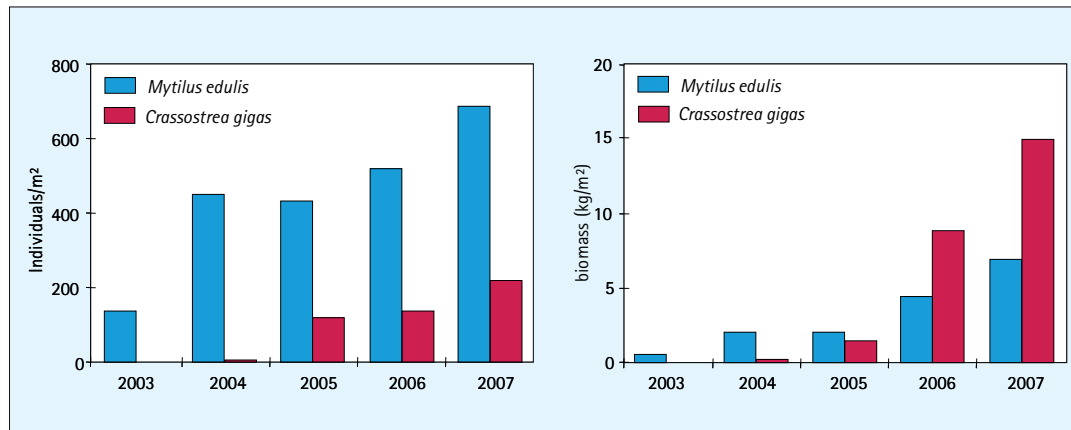
### Niedersachsen

First Pacific oysters in Niedersachsen were recorded in 1998 on an intertidal mussel bed near the island of Baltrum (Wehrmann *et al.*, 2000). Ten years later, Pacific oysters were found on all intertidal mussel beds in Niedersachsen. In 2003, only the western mussel beds reached marked abundances with up to 40 ind./m<sup>2</sup>. In 2004 and 2005, Pacific oyster distribution and increasing abundances followed a gradient from high abundance in the west to low abundance in the east (Brandt *et al.*, 2008; Schmidt *et al.*, 2008). Especially after a strong spatfall in 2006, abundances were increasing in the eastern parts as well. Maximum abundance then reached 2,228 ind./m<sup>2</sup> in 2007. Maximum mean abundance in 2007 was 746 ( $\pm$  667) ind./m<sup>2</sup> on an intertidal mussel bed in the Jade. Average abundance calculated for the tidal flats of Niedersachsen was 256 ( $\pm$  210) ind./m<sup>2</sup> in 2007 which corresponds to a mean biomass of 7.1 ( $\pm$  6,0) kg/m<sup>2</sup> (total wet weight). Total biomass in 2007, calculated for a total mussel bed area of 1,069 ha in Niedersachsen, is 75,500 t total wet weight (Wehrmann *et al.*, 2009). Compared to data from the Easter Scheld estuary and Schleswig-Holstein, mean values for biomass still seem to be at a lower level as invasion started much later in Niedersachsen. However, after a lack of spatfall in 2007 a strong spatfall was recorded in summer 2008.



Figure 10:  
Aggregation of Pacific oysters and blue mussels on an intertidal mussel bed in Niedersachsen where both ecosystem engineers, *Mytilus edulis* and *Crassostrea gigas*, are forming the shared habitat (Photo: A. Markert).

Figure 11: Development of abundance (individuals per m<sup>2</sup>) and biomass in kg total wet weight (TWW) per m<sup>2</sup> of blue mussels (*Mytilus edulis*) and Pacific Oysters (*Crassostrea gigas*) on a mussel bed in the Jade, Niedersachsen.



So far, Pacific oysters reach a maximum length of 30 cm. The presence of dead oysters is increasing as oysters stay cemented to their substrate. The ratio living/dead stayed  $\pm$  constant at 1:1 but shell weight (length and/or age) of dead oysters increases and is already dominating the western mussel beds (Wehrmann *et al.*, 2009). Mussel bed areas with high oyster densities are characterized by increased habitat matrix and tend to increase in relief developing pronounced mounds (patches) and pools (open spaces).

Almost all intertidal mussel beds in Niedersachsen are mixed beds (Figure 10) with increasing densities of Pacific oysters as well as blue mussels. Blue mussels on sites densely colonized by oysters may show higher abundances than oysters, but oysters are dominant in forming the shared habitat (Figure 11).

### Schleswig-Holstein

In Schleswig-Holstein, the main distribution area of the Pacific oyster is located in the intertidal of the Lister deep and on the tidal flats between the islands of Amrum and Föhr. In 1999, first surveys for oysters, conducted in the Lister Deep (first record in 1991), resulted in average densities of about 4 ind./m<sup>2</sup>. Since that time, oysters have spread successfully in their new habitat. As a consequence, nearly all blue mussel beds of the Lister intertidal have been turned into Pacific oyster bedss over the years. In 2003, Pacific oysters reached densities of >100 ind./m<sup>2</sup> due to a considerable spatfall in 2002. In 2006, mean densities in the Lister Deep were 722 ( $\pm$  267) ind./m<sup>2</sup> with a mean biomass of 50 kg/m<sup>2</sup> (TWW). This is similar to the highest values in the Oosterschelde. Since 2005, Pacific oysters form massive bedss in the Lister deep. Pacific oysters settle mainly on mussel beds but since 2004 some larger areas with empty shells from former mussel beds were colonized.

In the area between Amrum and Föhr Pacific oysters appeared since 1998 in low densities. In 2004, higher abundances were recorded. In 2006 a strong spatfall was recorded in many areas of the Wadden Sea of Schleswig-Holstein.

Several tidal basins in Schleswig-Holstein show differences in spatial and temporal development. In the Lister Deep the spread occurred earlier and much stronger than in other places. This might be caused by the Pacific oyster cultures present in this area which potentially produces a large number of larvae. In other tidal basins oyster colonization occurred later. This is remarkable, for Pacific oysters being present in this region since 1995 and on nearly all intertidal mussel beds in 1998, although in low densities (<1 ind./m<sup>2</sup>). Recently, the change in species composition seems to be in an advanced phase between Amrum and Föhr. Going south from these two tidal basins, Pacific oysters are still found in low densities (1 ind./m<sup>2</sup>). Also, the spatfall in late 2006 appeared to be much less compared to the northern area. In 2006, about 95% of the oyster biomass in the Wadden Sea of Schleswig-Holstein was found in the Lister Deep (13,838 t), whereas oyster biomass on the tidal flats near Amrum was rather low (643 t) and negligible in the rest of the area. Due to the spatfall in 2006 the oyster biomass increased in 2007 to about 65 kg/m<sup>2</sup> in the Lister Deep and dropped again to 50 kg/m<sup>2</sup> in 2008 because of natural losses (mortality). In the Norderaue about 11 kg/m<sup>2</sup> were found in 2007 and the value reduced to 6.7 kg/m<sup>2</sup> in 2008.

### Denmark

Pacific oysters have been recorded in the Danish Wadden Sea since 1996, but until 2004 oysters were found in low densities with only few individuals per km<sup>2</sup> (Kristensen unpubl. data). In 2004, a strong spatfall of Pacific oysters on former

mussel beds in the Danish part of the Lister deep strongly enhanced the population growth. The biomass was estimated at 1,000 t. Kristensen and Pihl (2006) report biomass values (TWW) of Pacific oysters between 0 and 30.36 kg/m<sup>2</sup> in 2006. As a result of the growth of the Pacific oysters, biomass increased to 3,289 tons in the Danish Wadden Sea in 2006. The biomass of Pacific oysters has increased to 6,264 t in 2007 with local biomass values up to 71.5 kg/m<sup>2</sup> and about 1,500 ind./m<sup>2</sup> (Kristensen and Pihl, 2008). These biomass values are low in comparison to the other parts of the Wadden Sea.

#### 4.2 Definition of mussel/oyster beds

Boundaries between mussel beds and the surrounding intertidal flats are not always clear-cut, which can easily lead to differences in size estimates among individual observers. Therefore, several criteria have been developed in order to make standardized decisions on the boundaries of mussel beds when carrying out field surveys (Figure 12) (TMAP Monitoring Handbook 2008). These criteria have been used since 2002 and proved to be useful.

Fields of scattered mussels, consisting of individuals and small conglomerates, are not included in the definition of mussel beds. They are generally not able to form a sizeable biogenic structure. Nevertheless, fields of scattered mussel clumps may consolidate to mussel beds after new spatfall or by more mussels being washed to these areas, but most of them disappear within one or two years.

A new method to estimate bed area has been developed (Kristensen and Borgstrøm, 2006), where digitized aerial pictures are applied and only the areas with mussels within the "old" bed structure are measured. All "sand"-parts are omitted in the calculation (Figure 13).

Aerial photographs and ground-surveys are used to determine the location and size and shape of mussel beds. For good recognition of intertidal mussel beds on aerial photographs, a stereoscope should be used. On average more than 75% of the beds can be recognized when information is available on preceding years (Fey-Hofstede *et al.*, 2009b). For monitoring purposes, it is important to carry out photographic surveys in a well-defined

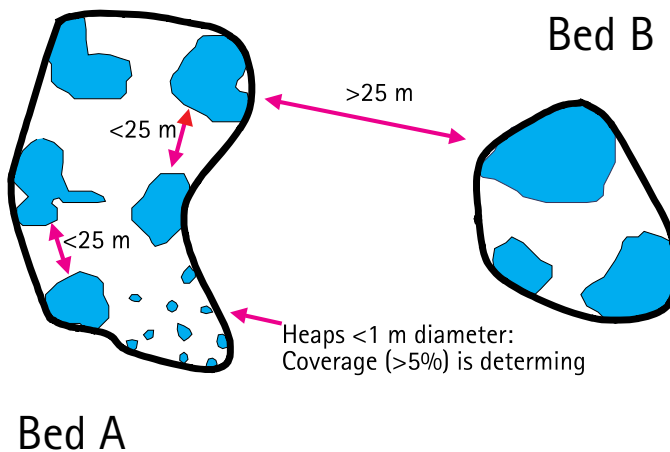


Figure 12: Blue mussel bed measuring protocol, with mussel patches (blue) and envelope (green).

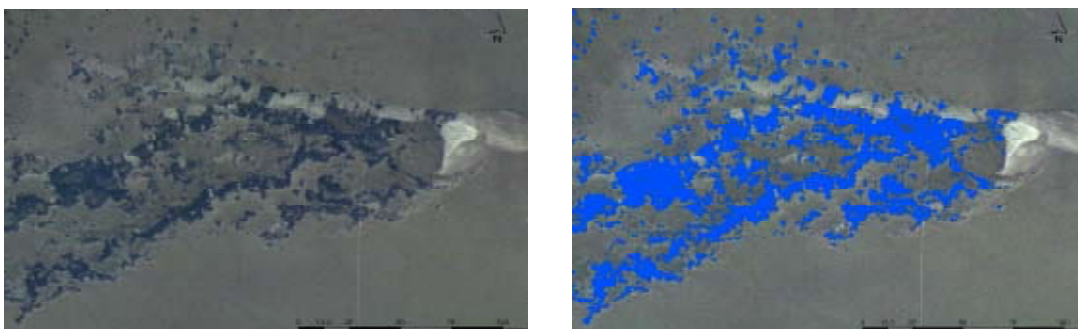


Figure 13: Scanned orthophoto of a smaller mussel bed in the Danish Wadden Sea (aerial photos from 2002, note: each pixel in blue is 0.16 m<sup>2</sup>). (From Kristensen and Borgstrøm, 2006).

time of the year because the surface covered by mussel beds can increase by spatfall during the summer months and will often decrease during autumn and winter due to storms and/or ice-scour. A relatively stable period is between March and July, after the winter and before new recruits can be detected on aerial photographs. Most of the maps of Dijkema (1989) were drawn from aerial photographs from this period. In The Netherlands (Ens *et al.*, 2004) and Niedersachsen (Herlyn and Millat, 2004), this period is recommended for aerial surveys of the surface covered with mussel beds. In Schleswig-Holstein, aerial photographs are intentionally made in autumn and therefore potentially include new spatfall.

#### Definition oyster beds/mixed beds

Pacific oysters and blue mussels often occur together, shaping the tidal flat as habitat builder in varying proportions. As they are different species and as the Pacific oyster is an introduced species, oyster beds should clearly be distinguished from blue mussel beds.

The question is when a wild bed is classified as an oyster bed or a mussel bed. Therefore a general

definition is needed. A first approach is to use the live wet weight as parameter. The species which dominates the biomass (live wet weight) of a bed should define the classification.

If no samples are taken for measuring the flesh weight, the dominance of either mussels or oysters on these beds should be classified from its visual appearance. To this end, the following scale of oyster density is proposed:

- 1: <30% (pure mussel bed with scattered oysters)
- 2: >30% - 60% (balance between mussel and oyster patches)
- 3: >60% (oyster bed with mussel patches)

### 4.3 Consequences for monitoring and assessment

Due to its rapid spread and current stock development during the last years, it is strongly recommended that the development of the Pacific oyster becomes subject of a detailed monitoring program, considering the monitoring requirements from the EU Habitat Directives and the EU Water Framework Directive.

## Definitions

### Mussel bed

A mussel bed is a benthic community structured by blue mussels. Similarly, an oyster bed is a benthic community structured by oysters. Both communities mix. Mussel and oyster beds may consist of a spatially well defined irregular collection of more or less protruding smaller beds, which may be called patches, separated by open spaces. This description also includes young beds with a high abundance of small mussels. The described structure may not be so distinct in young beds or newly-settled beds (spatfall) (Blue mussel workshop, 2002).

### Stable bed

Bed where the structure (patches, formed relief) is clearly recognizable over many years (Blue mussel workshop, 2003; QSR 1999).

### Stable site

Location where mature mussel beds (one or more) occur regularly over several years (Blue mussel workshop, 2002).

## Assessment criteria for persistence of a mussel bed

Age of bed, type of location, sediment structure of mussel bed basis (Blue mussel workshop, 2002).

### Larvae settlement

The first benthic migrating stage of blue mussel larvae smaller than 1 mm is defined as primary settlement. The larvae can settle several times on various substrates until they get larger and settle more permanently on structures such as existing mussel beds or stones (secondary settlement) (Blue mussel workshop, 2000).

### Spatfall

Settlement of young mussels or oysters on a tidal flat or in existing beds. These small bivalves are called 'spat' during the year of settlement only.

### Recruitment

The addition of young mussels to the reproducing population. For blue mussels, the concept of recruitment is used for young mussels which survived the winter (age = 1 year).

The following aspects are recommended for an annual monitoring program:

- total area covered by Pacific oysters,
- biomass (stocks' development),
- in selected areas: density, size structure and biomass of both, blue mussels and Pacific oysters,
- annual recruitment of blue mussels and Pacific oysters.

The resulting data will allow the most important aspects of stocks' development to be monitored. However, more detailed investigations on filtration rate, production and energy flow as well as studies of the associated benthic and bird community are highly recommended.

The monitoring of Pacific oyster beds can in many aspects follow the standards defined for blue mussel monitoring implemented in the Wadden Sea (TMAP Monitoring Handbook 2008). Like the blue mussel beds, oyster beds can be identified from aerial photos. However, they cannot be distinguished from each other, thus additional ground-based investigations are necessary. Aerial pictures can be either made in spring or autumn. Different methods are used to determine the coverage (patches per bed). Similarly to blue mussel beds, oyster beds can be mapped at the tidal flats with the so-called 'Stiefelmethode' which means walking along transects over the mussel bed and counting the steps on mussels and bare sediment. Length and position of the transects may be tracked using a GPS. Sampling of oyster beds might need slightly larger frames than those used for blue mussels. In the monitoring program in the Wadden Sea National Park of Schleswig-Holstein

a 25 cm x 25 cm frame is now used to sample both species and it is recommended to use it as a standard for further monitoring (TMAP blue mussel expert meeting, Wilhelmshaven September 2007). In Niedersachsen, the 'Stiefelmethode' is applied using a 25 cm x 25 cm frame for both species since 2008. In The Netherlands some specific beds are monitored with a 15.5 cm x 32 cm frame, and the majority of beds with sampling devices covering 0.4 or 16 m<sup>2</sup>.

Samples may be taken randomly over the entire bed or in the covered heaps only if coverage of the bed is assessed in the same time. Sampling can best be carried out in the period between summer and autumn to monitor the oyster spatfall that has survived the winter.

Biomass of Pacific oysters could be measured as cooked flesh weight (g/m<sup>2</sup>). Total wet weight, which is often used in the monitoring of blue mussel is useful, however, data from both species cannot be compared directly as the flesh content of oysters is lower than that of blue mussels, and a reef can consist of many dead shells which are inseparable cemented together with live specimens.

Currently, the monitoring of Pacific oysters in the Wadden Sea is not done in a harmonized way, e.g. no specific monitoring was conducted in the Dutch Wadden Sea in 2007 and 2008, whereas further assessments in Niedersachsen and Schleswig-Holstein are continuing. Such gaps should be filled as soon as possible by establishing a regular monitoring within the framework of the TMAP. Additionally, an extension of the surveys to the subtidal is essential, because the Pacific oyster spreads rapidly into this area as well.

## 5. Change in mussel bed community

Mussel beds provide a habitat for a diverse community of both endo- and epi-fauna, with higher densities and biomass as compared to surrounding tidal flats (Asmus 1987). Community structure has been changing with decreasing mussel densities and the transition of mussel beds to oyster beds, however, oysters offer a similar habitat for associated fauna (Büttger *et al.*, 2008, Markert *et al.*, 2009).

Oysters are not the only invasive species settling on mussel beds. The rate of species introductions is continuously increasing worldwide. Especially, the Wadden Sea area is very receptive to introductions of non-indigenous species. There is a high number of alien species in the Wadden Sea that have established successfully on mussel beds, some of which have significant effects on the populations of native species (see also QSR 2009 Thematic Report 7 "Alien Species").

Figure 14 gives an example of the proportion of non-indigenous and native species of two mussel bed areas in the Wadden Sea of Schleswig-Holstein.

On the tidal flats of the Wadden Sea, mussel beds naturally provide the only suitable biogenic hard substrate for the attachment of sessile epibenthic species (natives as well as alien species). The most important non-indigenous species which established successfully in the Wadden Sea and occur especially in high densities on mussel beds are the Pacific oyster *Crassostrea gigas*, the American slipper limpet *Crepidula fornicata* and the Australian barnacle *Elminius modestus*. Over the last decades, two algae species have also invaded the Wadden Sea: the Japanese seaweed *Sargassum muticum* and the red macro-alga *Gracilaria vermiculophylla*. Most recently, the non-native Asian crab of the genus *Hemigrapsus* which invaded the Easter Scheld estuary in 2000 has been recorded in the Dutch and German Wadden Sea.

*Crepidula* used to be rare in the Dutch Wadden Sea and more common in Germany. It has spread out in the entire Wadden Sea area. In the last decade, *Crepidula* has locally established dense layers on mussel beds in the low intertidal and

the shallow subtidal, but the development seems to have little effect on mussel beds (Thieltges *et al.*, 2003; Nehls *et al.*, 2006; Wehrmann and Schmidt, unpubl.).

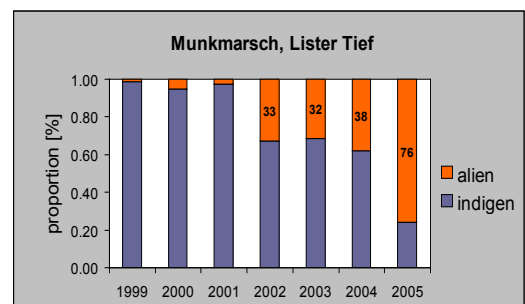
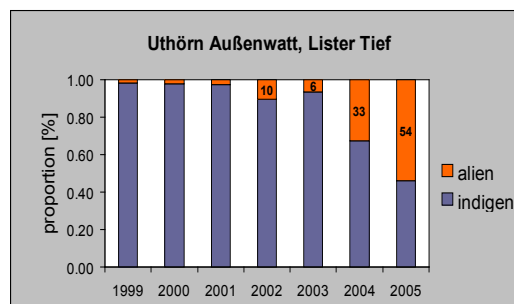
In the years following its introduction into the Wadden Sea, *Elminius modestus* has extended its range slowly. In the intertidal area of the northern Wadden Sea, population density grew significantly within the last two years, but has presumably not reached its maximum yet (Witte *et al.*, submitted).

*Sargassum muticum* has presumably been introduced with oysters and spread rapidly along the European coasts. In the Wadden Sea, *Sargassum* occurs mainly epizootically attached to mussels and especially oysters in the shallow subtidal zone. Tolerating a wide range of abiotic conditions, it is considered to be highly invasive (Nyberg and Wallentinus, 2005). However, in the Wadden Sea it provides an additional highly structured habitat with facilitating effects for native algal, invertebrate and fish species (Buschbaum *et al.*, 2006; Polte and Buschbaum 2008).

Algae of the genus *Gracilaria* were first noticed in the Dutch Wadden Sea around 1990, but species information are not available. It was fairly common but not considered a problem nor covering vast areas. Less than 5 years following its first observation in the German Wadden Sea, the invasive species *Gracilaria vermiculophylla* is common in many regions. In Schleswig-Holstein, the algae has strongly spread after 2003 and covered many mussel beds with dense layers, but since 2007, development has been stable or even decreasing. The algae occurs in all intertidal habitats of the Wadden Sea but reaches highest densities on mussel beds (Buschbaum *et al.*, 2008) and cockle beds (Dankers, unpubl. data).

In 2006, first specimens of the Asian crab *Hemigrapsus* were found on a mussel bed in the Dutch Wadden Sea and on a westernmost oyster bed in the Wadden Sea of Niedersachsen (Markert, unpubl. data). In 2007, grapsid crabs were reported from several locations in the whole German Wadden Sea. The spread of *Hemigrapsus* will be tracked in Niedersachsen.

Figure 14:  
Proportion (individuals)  
between introduced and  
native species on two mus-  
sel beds near the island of  
Sylt, Schleswig-Holstein.



## 6. Factors influencing mussel bed development

### 6.1 Recruitment success

The establishment of new blue mussel beds has been a rare event for almost a decade in most parts of the Wadden Sea, except for the Netherlands. After the cold winter 1995/96 many blue mussel beds were replenished by a strong spatfall in summer 1996 and again in 1997. In the following years, very limited spatfall occurred and only a few blue mussel beds were recovered or had increased in size (Strasser *et al.*, 2001b). Spatfall into existing beds was noticed but it was too insufficient to allow a stable population. Only in the Dutch part of the Wadden Sea there was an appreciable spatfall into existing beds and establishment of new beds. However, blue mussel beds are decreasing in most parts of the Wadden Sea; even small losses in mussel bed area are apparently not compensated by spatfall. As a result, annual losses accumulate and lead to a permanent decrease. The mechanism behind the influence of winter severity on recruitment success is poorly understood. The failure of recruitment may be initiated by mild winters, resulting in a synchronized settling of mussels and the occurrence of their main predators in the Wadden Sea. Variability in predation on postlarvae is presumably contributing to the annual variability in recruitment. On tidal flats, epibenthic predation pressure in spring and early summer is related to preceding winter's temperatures: after cold winters, both seasonal arrival on tidal flats of epibenthic predators such as shrimps and shore crabs takes place later in the year as well as in lower numbers, minimizing predation pressure. Additionally, a succession of warm summers is expected to lead to an overgrowth of mussel beds by the Pacific oyster which is expanding its range rapidly facilitated by high summer temperatures (Nehls *et al.*, 2006). Observations in all Wadden Sea areas show that in the long run existing mussel beds would disappear when recruitment is low (Fey *et al.*, 2008a, 2009c). Besides, the total surface of beds will diminish due to storms and ice cover as long as these losses are not compensated by new settlement.

The proceeding global climate change is leading to an increase in surface water temperatures which again facilitates specifically warm-water species such as the Pacific oyster, allowing these species to successfully reproduce in the presence of potential predators. In a warming Wadden Sea, cold winters occur less frequent and so does good recruitment of blue mussels.

### 6.2 Impact of fisheries/ mussel farming on intertidal mussel beds

In The Netherlands, mussel stocks and natural beds crashed in the early 1990s due to overfishing. Since 1995, there was almost no impact of mussel fishery on the intertidal area. Seed mussels which are used to stock the culture lots have been obtained from subtidal areas. Following the prohibition of mussel fishery, mussel stocks of the intertidal have recovered slowly. The landings increased slightly for some years, but have not reached former levels yet (Ens *et al.*, 2004). In all other parts of the Wadden Sea, natural beds of the intertidal have decreased for a decade now and so have mussel landings. It is not clear, to what extent the harvesting of seed mussels has contributed to the decline of the natural stock. Intertidal mussel beds in Schleswig-Holstein are declining although there has been no impact of mussel fishery in the intertidal since 1995. Hence, the loss of mussel stocks here must have other causes. In Niedersachsen, the management plan for mussel fishery is being renewed with the intention to protect mature beds in balance with economic fishery interests (Herlyn *et al.*, 2008). However, the fishing of seed mussels in intertidal areas will still be allowed, although investigations of stable sites of blue mussel beds in the Niedersachsen Wadden Sea showed that in most cases mussel fishery led to heavy or even complete losses which have been larger than the amounts of mussels actually removed by fishery (Herlyn and Millat, 2000). In Denmark, mussel fishery is allowed only in about 50% of the Danish Wadden Sea since 1992. These areas contain intertidal as well as subtidal beds, the latter being preferred by the fishermen. As a consequence, the intertidal beds in the Danish Wadden Sea have not been fished since 1992.

In conclusion, it can be stated that in The Netherlands, in Schleswig-Holstein and in Denmark the direct impact of mussel fishery on the natural development of intertidal mussel beds has been limited or absent in recent years. Only in Niedersachsen does mussel fishery in the intertidal area continue.

### 6.3 Detrophication

Considerable effort has been made over the last decades to reduce nutrient inputs to rivers and North Sea. There have been discussions whether

an impact of reduced nutrient loads already affect primary production of the Wadden Sea and consequently biomass of filterfeeders as mussels. At present, there is no evidence that mussel growth and population dynamics are affected by detrophication. However, this aspect should be watched closely in the future as impacts are likely to occur.

#### 6.4 Pacific oyster invasion

Beds of blue mussels provide a suitable hard substrate for settling oyster larvae and are considered to be the main reason for the rapid expansion and successful establishment of *C. gigas* in the Wadden Sea. Several studies showed that the abundance of blue mussels apparently remains on a stable level even in dense Pacific oyster beds. However, densities have decreased and the biomass of blue mussels in these beds is now much lower than it was before Pacific oysters were present. According to that, decline of the blue mussel populations may particularly be ascribed to the wide spread of *C. gigas*, but in fact, mussel stocks have decreased already before the Pacific oyster started to spread

out. In addition, loss of blue mussel populations did not vary between areas where oysters occurred and areas where they have been absent. Thus, the spread of *C. gigas* cannot be related to the reason for the decline of the mussel stocks in the Wadden Sea so far (Nehls and Büttger, 2007). The Pacific oyster obviously has established a stable population in the Wadden Sea. Further spread of the oyster population is expected and might lead to a functional change in the Wadden Sea and in the whole associated community. A complete displacement of blue mussels by oysters is not expected. There are several examples of co-existence of blue mussels and oysters on mixed beds. In some regions with good blue mussel spatfall, the occurrence of oyster beds is relatively small. A spreading of the Pacific oyster into the subtidal area cannot be excluded. This is an ongoing process and further development cannot be predicted (Nehls and Büttger, 2007). In that case, mussel recruitment may be reduced, because of predation by oysters that filter mussel larvae from the water column (Troost, 2004).



## 7. Conclusions

To protect intertidal blue mussel beds, considerable parts of the intertidal area of the Wadden Sea have been permanently closed for mussel fisheries. Differences between the three countries in measures to increase the area of naturally developing mussel beds as well as in the results are substantial. In The Netherlands arrangements have been successful: intertidal mussel beds have recovered in a few places, but have not reached former levels. Contrary to the Dutch Wadden Sea, mussel beds in Niedersachsen, Schleswig-Holstein and Denmark decreased in the last decade. In these countries the last considerable spatfalls occurred in 1996 and 1997, leading to establishment of beds at a large scale, whereas the establishment of new beds occurred only locally after this.

The contrasting developments of natural mussel beds lead to uncertainties regarding the causes of recruitment failure in most areas of the Wadden Sea. Predation on the spatfall seems to be the most important, which again is facilitated by climate change. It is assumed that annual variation in predation rate and recruitment success relates to winter temperatures: cold winters result in low predation rates because the main predators of bivalve spat (*e.g.* shrimp and shore crab) return later in spring to the tidal flats. As a consequence, the bivalve larvae can establish successfully. By contrast, warm winters lead to high predation rates and low recruitment success.

In the same time, Pacific oysters spread out very strongly, facilitated by climate change which in turn is leading to more favourable conditions for this species. By now, oysters have densely colonized many former mussel beds in the Wadden Sea, but there is no indication that their spreading has caused the recent decline of the blue mussels in the Wadden Sea. Several studies showed that coexistence might be possible, but the questions whether or not native blue mussel beds will disappear over time due to the rapid spread of the Pacific oyster cannot be answered so far (Diederich, 2005; Betz, 2007). There are several examples of co-existence of blue mussels and oysters in mixed beds. In the Dutch Wadden Sea, blue mussels have successfully re-established a strong population in the last years. If sufficient blue mussel recruits manage to settle, new beds may develop and blue mussels may co-exist with oyster beds.

Knowledge on the ecology of natural subtidal mussel beds of the Wadden Sea is scarce. However, intertidal and subtidal mussel beds seem to differ in (1) biogenic bed structure, (2) species interactions and (3) associated organisms. The ecosystem of subtidal beds is potentially more diverse than on intertidal beds, but further investigations are needed. The main known subtidal mussel beds are in the western Dutch Wadden Sea, in the Schleswig-Holstein area and Ho Bugt in Denmark.

## 8. Target evaluation and recommendations

### 8.1 Target evaluation

After a period of intensive fishing of many intertidal mussel beds and relatively low mussel stocks, a specific trilateral target was formulated, aiming for (1) an increase of the area and (2) a more natural distribution and development of natural mussel beds. Since then, strict regulations have been applied in most of the areas.

Referring to several long-term investigations, it can be concluded that despite considerable efforts in mussel management, the target of increasing mussel bed areas in the intertidal has not been achieved in three out of four subregions in the Wadden Sea. Only in the middle and the eastern part of the Dutch Wadden Sea an increased area was reached, whereas in all other parts of the Wadden Sea total area of mussel beds is still below former levels. This does not lead to the conclusion that management has failed over the last decade, as the development of mussel stocks is not only influenced by fisheries but subject of considerable natural variation and most probably effected by long-term changes of the climatic conditions.

With regard to the subtidal mussel beds, an evaluation of the target is still not possible.

The target of a more natural distribution and development of intertidal mussel beds has been achieved in all areas which have been closed for mussel fishery, however, increasing proportions of alien species indicate that a natural development today is influenced by factors acting on larger scales and cannot be achieved only by regulations within the Wadden Sea.

### 8.2 Recommendations

More research needs to be done both in relation to natural dynamics and long-term changes of intertidal and subtidal mussel beds in the Wadden Sea as well as on the impacts of fisheries. Impact studies on mussel fisheries are still rare and not yet sufficient to draw general conclusions.

The further development of the Pacific oyster and its possible effects on the Wadden Sea ecosystem should be subject of an annual research and monitoring program. Monitoring standards should be harmonized within the entire Wadden Sea and comply with the objectives of the EU Habitats Directive as well as of the EU Water Framework Directive. Pacific oyster monitoring should be included in the existing monitoring of blue mussel beds, which requires extra funding.

Nature conservation targets and habitat definitions have to be clarified and a procedure to classify mussel beds as habitats according to the new definitions has to be developed.

Conservation targets have to be evaluated against the background of a changing Wadden Sea where increasing temperatures are in favour of a marked change from mussels to Pacific oysters and detrophication may induce a decreasing trend in productivity.

The management measure of protecting stable mussel beds or sites is still valid.

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