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Aerial surveys, biomass estimates, and elimination of the mussel population (*Mytilus edulis L.*), in the Danish Wadden Sea, 1991-1994.

by

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1. Abstract

In 1991 and 1993, the Forest and Nature Agency and Danish Institute for Fisheries Research, performed an aeroplane photo survey of all the gullies in the Danish Wadden Sea, to identify areas with mussels (*M. edulis*). The main areas with mussels were found in Ho Bight in the northern part of the Danish Wadden Sea. From 1991 to 1993 a decrease of mussel bed areas were observed. The total area with mussel beds registered in 1991 in the Wadden Sea was 10.92 km^2, and in 1993 only 8.67 km^2. The subtidal areas increased from 1.8 km^2 in 1991, to 2.5 km^2 in 1993, and the intertidal area decreased from 9.1 km^2 in 1991, to 6.2 km^2 in 1993.

To verify the aeroplane observation, samples of mussels were collected in the beds in 1991, 1992 and 1993. The densities (no./m^2) of mussels in Ho Bight varied considerably throughout the investigation between 0 and 3 800 mussels/m^2, and the biomass varied between 0 kg and 63.9 kg per m^2. The biomass in the samples was in 1991 in average 7,1 $\pm$6,0 kg per m^2 (mean $\pm$2 SE; n=14). The biomass in the samples in 1992 was in average 17,0 $\pm$10,3 kg per m^2 (mean $\pm$2 SE) and in 1993 in average 19,5 $\pm$ 7,8 kg per m^2 (mean $\pm$2 SE; n=32).

The total biomass of mussels in the Danish Wadden Sea increased over seven years from 15 500 metric tonnes in 1988, to 90 000 metric tonnes in September 1993. In September 1994 the standing stock (subtidal and intertidal) in the Danish Wadden Sea was 117 000 metric tonnes.

In the period 1991-1994, 4 628 metric tonnes of mussels ($\geq$ 5 cm in shell length) were fished annually in the Danish Wadden Sea.

Eiders, herring gulls and oystercatchers in the Danish Wadden Sea feed primarily on mussels and may consume up to 16 000 metric tonnes of mussels annually (equal to ~ $17 \star 10^6$ bird days).

The elimination of mussels (Z=M+F) from 1991 to 1993 is estimated to be as high as 60 000 metric tonnes, or 20 000 metric tonnes annually. 3/4 consumed by the birds (M) and 1/4 catched by the fishermen (F).

2. Introduction.

In 1961-65, Theisen (1968) performed an experimental transplantation of mussels in the Danish Wadden Sea, similar to what has been undertaken in the Dutch and German Wadden Sea for decades. His investigations did not result in culture of mussels in the Danish Wadden Sea. So, today transplantation and culture of mussels or other marine bivalve species is prohibited according to the legislation for protection of the Danish Wadden Sea. Only fishing on the natural stocks of mussels may take place in the Danish Wadden Sea.

The Danish Wadden Sea has been exploited by commercial fishing of mussels (*Mytilus edulis L.*) for the last 16 years (Fig. 1). The landings from 1979-1994 varied annually between a few hundred tonnes (1979-1982) to more than 27 000 metric tonnes in 1985. Unofficial figures for the landings in 1985 indicated values of 75 000 metric tonnes (Kristensen, 1994, information given by mussel fishermen). A total of 90 000 metric tonnes of mussels were landed from the Danish Wadden Sea between 1983 and 1987.

The intensive fishery of mussels, and the destruction of a large number of intertidal mussel beds during the ice winter 1986/87 resulted in a collapse of the mussel stock in the Danish Wadden Sea in spring 1987. During the summer and autumn 1987 a large spat-fall took place in the Ho Bight (Munch-Petersen and Kristensen, 1987 and Munksgaard, 1989). The 87-cohort of mussels in the subtidal beds had reached the fishing size in the summer 1990 (shell length ≥ 5 cm, and >90% of the mussels suitable for fishing).

The fishery of mussels in the Danish Wadden Sea has all the years been secondary compared to the main fishing area for mussels in Denmark, Limfjorden, where the annual landings the last five years have been around 100 000 metric tonnes (Kristensen, 1994).

The mussel stock in the Danish Wadden Sea was assessed for the first time in the autumn 1986 (Munch-Petersen and Kristensen, 1987), following the comprehensive fishery in the years 1983-1986 (Fig. 1). The areas with mussel beds were identified by use of aerial photos (black and white pictures). Since the photos were not taken with the purpose to distinguish mussel beds, problems with the interpretation arose (Munch-Petersen and Kristensen, 1987 and Munksgaard, 1989).

In 1988, the Danish Institute for Fisheries and Marine Research investigated the use of aerial photos in colours to quantify areas with intertidal mussel beds in the Danish Wadden Sea (Munch-Petersen and Kristensen, 1989). The pictures were analysis, and the biomass (kg/m^2) of mussels within the mussel beds estimated. There was a weak correlation between the grey tone values, and the biomass of mussels in the investigated area. However, use of aerial photos in colour to detect the mussel beds and their size was more useful, than the aerial photos in black and white used in the assessment in 1986 (Munch-Petersen and Kristensen, 1989).

In the autumn 1990 it was decided to perform an investigation of the mussel stock, and to ascertain the impact on the mussel stock from mussel fishing in Ho Bight (Hjerting Stream only). The purpose was to find the size of the mussel beds by aerial photo surveys, and to assess the biomass of mussels in the mussel beds. Secondly, to evaluate the annual production (P) of mussels in the Danish Wadden Sea, for which figures from the literature (Asmus, 1987) was used. The estimate was based on the estimated standing stock (B) in this investigation. For the third, to evaluate the importance of F (the fishing mortality) and M (the bird predation, assumed to be 50% of the total mortality) for declines/increases in the standing stock of mussels in the Danish Wadden Sea.

3. Material and methods.

In Ho Bight, with the two tidal gullies Hjerting Stream and Hobo Deep several mussel spats settled in the summer 1987. (Munch-Petersen and Kristensen, 1987 and Munksgaard, 1989).

In Hjerting Stream, the mussel areas were divided into three sectors with a total biomass of mussels of around 15 700 metric tonnes in the May 1991 (Tab. 3). The three areas were different in extent, and in size of the mussel stocks (Fig.2 and Tab. 3).

Sector 1:	8 km^2	Fishing: 1. October - 31. April each year.
Sector 2:	2 km^2	Fishing: 15. July - 1. October each year.
Sector 3:	7.3 km^2	Fishing: No fishing

3.1. Estimating the size of the mussel beds.

All gullies in the Danish Wadden Sea were photographed in 1991 and in 1993. The intertidal mussel beds, which were farthest away from the gullies, were not photographed, because they are of no interest in the management of the fishery of mussels.

The aeroplane photo survey was carried out by a consultant company (Jan Kofod Winther, Luftfoto). Photographing was only successful at low tide, when there were no wind, no clouds, and only if the sun was high on the sky, which only happens few times during the summer time.

A Cessna 172 plane was used. The flying altitude was 4 500 feeds (~1 350 m). A camera model 500 ELX Hasselblad was used (lens: 40 mm, Zeiss, distagon). The films used, were kodak aerochrome or kodak ectochrome. Slides were made from the negatives, 56 mm x 56 mm. Afterwards, paper pictures were made of the slides, 200 mm x 200 mm.

An overview picture was constructed by use of all the paper pictures, to form a map of the Wadden Sea , and to distinguish the potential mussel beds. Areas with mussel beds were distinguished by their colour (dark areas), from areas with sand (light coloured). Sampling of mussels on the assumed mussel beds in the felt was conclusively used to verified the aeroplane observations.

Each aerial photo covered about one minute of arc = 1 852 m. Each slide or paper picture therefore covers 1 852 $\star$ 1 852 m^2 = 3 429 904 m^2. Both in 1991 and 1993 a building of specific size could be distinguish on the paper pictures. From those, the scale in 1991 was estimated to 1:10 000, and in 1993 to 1:9 481.

From the map constructed from the paper pictures, the felt verified areas with mussel beds, were cut out in tracing paper. The pieces representing mussel beds were all weighed on a Mettler PM 4600 Delta Range weight (accuracy: 0.01 g equal to one hectare (10 000 m^2)). Two cut pieces of tracing paper (10 $\star$ 10 cm^2 for the 1991 pictures, and 9.5 $\star$ 9.5 cm^2 for the pictures from 1993) were used to transform one m^2 of mussel bed to weight.

3.2. Density and biomass of mussels (no./m^2 and kg/m^2).

Mussels were sampled from 32 different sampling stations regularly spaced and stratified in the three sectors 1, 2 and 3 (Fig.2). Within a frame of 0.25 m^2 all mussels and shells of mussels were collected by a diver. At sampling, the diver judged the area covered with mussels within the vicinity of the sampling station (~ 100 x 100 m) in the intertidal mussel beds. The samples were weighed on a steelyard weight (accuracy: 0.25 kg). A random subsample around 3 kg (at least 150 live mussels) was taken from the gross sample and frozen for later analysis.

In the laboratory the subsamples were sorted in fractions of live mussels, and shells of different bivalves and gastropods, and invertebrates. The fraction of live mussels in the samples was determined, and used to estimate the density of mussels on the sampling station, in numbers, and the biomass of live wet weight of mussels/m^2. The shell length of the mussels was measured in mm. Data analysis was carried out in EXCEL 5.0 and SAS (plot and GLM-routines).

The sampling stations in the subtidal mussel beds were spaced randomly and represented both areas with, and without mussels, and the average density of mussels was used directly, to estimate the biomass of mussels in the various beds.

The density of mussels measured for the mussel beds in the Hjerting Stream have been used to estimate the stock size in the three other tidal areas in the Danish Wadden Sea (Knude Deep, Juvre Deep and Lister Deep).

3.3 Sampling by dredge.

In September 1994 all mussel beds identified in the 1993 aeroplane photo survey in the three tidal areas in the Danish Wadden Sea were dredged by a commercial vessel to collect samples of mussels. The purpose was to determine the biomass (kg/m^2) of the mussel stocks in the entire Danish Wadden Sea. Secondly, to compare the dredging technique with the diver sampling technique used in the stock survey the previous years in Hjerting Stream. Dredge samples were taken at 79 different stations (Tab. 6). Fifty two samples were taken in Grey Deep at Esbjerg, nine in Knude Deep, and twelve in Lister Deep. It was not possible to take dredge samples in Juvre Deep in September 1994.

The hauling speed was two knot, and the hauling time varied between 4 and 159 seconds (Tab. 6). The commercial dredge is 1.8 m wide, and a haul could therefore be estimated to cover between 7.408 m^2 and 294.47 m^2. The catch in each haul was judged by the skipper and the research assistant (if there was disagreement between their two judgements an average figure was chosen). A subsample was taken from the gross catch and frozen to be analysed in the laboratory. The number of live mussels in the frozen subsample was measured. By unfreezing, the mussels loose in average 20% of their wet weight, which has to be added to the mussel weight before the fraction of live mussels in the catches can be estimated. The density (kg) of mussels in total wet weight per m^2 was estimated for each sample taken by dredge.

The biomass of the standing stock of mussels in each tidal area (4) was estimated by multiplying the average biomass of mussels (kg/m^2) with the total area of mussel beds (m^2) in each tidal area determined on the aeroplane pictures from 1993. To estimate the standing stock of mussels in Juvre Deep, the average density-estimates for the mussel beds in Grey Deep, Knude Deep and Lister Deep was used.

3.4. Estimation of food demands of birds.

The mussel stock in the Danish Wadden Sea is consumed by a number of bird species. The most characteristic mussel eating birds are the oystercatcher (*Haematopus ostralegus*), the eider (*Somateria mollissima*), and the herring gull (*Larus argentatus*).

Based on figures from the literature the three bird populations consumption of mussels are estimated. The oystercatcher has a daily average energy demand of 833 kJ/day (Goss-Custrad and Durell, 1987), which is equal to around 38 g AFDW mussel meat (22 kJ/g AFDW of mussel meat; McLusky, 1989). The eider needs 2732 kJ/day (Swennen, 1976, Nyström and Pehrsson, 1988), which is equal to 124 g AFDW of mussel meat. The herring gull has a daily demand of energy of 1987 kJ/day (Faldborg et al, 1994), which is equal to 90 g AFDW of mussel meat. The energy demands are used to calculate the number of birds (bird days), that can be sustained on the annual production of mussels (50% of P) in the Danish Wadden Sea.

4. Results.

4.1. Estimating the area of the different mussel beds.

Estimates of the area of the different mussel beds in the Danish Wadden Sea detected from the aerial photos are shown in Table 1.

In both 1991 and 1993 the largest areas with mussel beds were found in the Hjerting Stream (the fishing sectors). The mussel beds respectively represented 38% in 1991, and 46% in 1993 of the total area of mussels in the Danish Wadden Sea (Tab.1).

On the photos, the mussel beds are spaced in groups. The total area of mussel beds in the Danish Wadden Sea is estimated to 10.92 km^2 in 1991. The intertidal beds covered 9.13 km^2, and the subtidal beds 1.79 km^2. The total area (8.67 km^2) with mussel beds in 1993 was smaller (21%) compared to 1991. The size of the intertidal beds was 6.19 km^2, and 2.48 km^2 were subtidal mussel beds. Conclusively, the total area of intertidal mussel beds declined from 9.13 km^2 in 1991 to 6.19 km^2 in 1993, a chance of 32%. Simultaneously the subtidal beds grow from 1.79 km^2 in 1991 to 2.48 km^2 in 1993, and with 38%.

The decline of mussel beds in the Danish Wadden Sea is masking over a large variety of declines and increases in the different tidal areas, and over differences between the various intertidal and subtidal mussel beds. The biggest chance was found in Juvre Deep among the intertidal mussel beds, which declined ca 64% from 2.69 km^2 in 1991 to only 0.96 km^2 in 1993 (Tab. 1).

In the fishing sectors in Hjerting Stream, the mussel beds covered 4.14 km^2 in 1991 (exclusive the beds in Hobo Deep west of Langli, 1.23 km^2) of which 3.05 km^2 were intertidal mussel beds, and 1.09 km^2 were subtidal mussel beds (Tab.1). From 1991 to 1993, the area with intertidal mussel bed decreased from 3.05 to 2.03 km^2 or 33%. Simultaneously, the subtidal mussel beds increased from 1.09 to 1.98 km^2 or 82%. There were not detected any intertidal mussel beds in fishing sector 3, neither in 1991 nor in 1993 (Tab. 1).

From 1991 to 1993 the total area with mussel beds in Ho Bight was reduced by 12%. In the fishing sectors the reduction was only 3% from 4.14 km^2 to 4.01 km^2 (Tab.1). In sector 1, where the fishing from 1991 -1993 annually amounted to 25% of the annual estimated standing stock, the area with mussel beds increased 10%, from 2.78 km^2 in 1991 to 3.07 km^2 in 1993 (Tab. 1). In sector 2 (fishing 10% of the annual standing stock) the area with mussels decreased 58%, and in sector 3 (without fishing) the area with mussel beds increased 78% (Tab.1).

4.2. Densities (no./m^2).

In 1991 the density (range) of mussels, in the three fishing sectors in Hjerting Stream were between 0 and 1 000 per m^2. The highest density (~ 3 800 mussels/m^2) of mussels was found in sampling station 31 (an intertidal mussel bed) in fishing sector 1, and in sampling station 13 in fishing sector 3 (a subtidal mussel bed). Both sampling station 1 and 26 (sector 1, subtidal beds) showed a density of mussels of max. 2 000 per m^2. In all other stations the maximum number of mussels was ca 1 500 per m^2.

In sector 1, four sampling stations were without mussels, and in sector 2 all sampling stations had mussels. In sector 3, 4 sampling stations were without any mussels. The smallest number of mussels per m^2 was found in August 1992 and in July 1993 in sample station 12 (sector 3), and in October 1991 in sampling station 22 (sector 1), where only 150 mussels per m^2 were found. The density of mussels in the mussel beds varied, both from sector to sector, and from sampling station to sampling station, within the sectors. So, there was no distinct pattern for the variation, whether the mussel beds were intertidal or subtidal, fished or not fished.

4.3. Biomass (total wet weight) (kg/m^2):

To estimate the biomass of mussels, it was necessary to estimate the density (kg) of mussels + shells per m^2 from all the sampling stations, and to estimate the fraction of mussels in the samples. The biomass varied (range) between 0 kg and 63.9 kg/m^2 in the 1991, 1992 and 1993 samples. The largest biomass was found in sampling station 31 in fishing sector 1 in September 1993 (63.9 kg/m^2).

The average biomass estimated from each survey in the different fishing sectors are shown in Table 2. From 1991 to 1993 there was an increase in the average biomass of mussels in all three sectors. The annual average biomass in all three sectors was in 1991, 7.1 $\pm$ 6.0 kg/m^2 (mean $\pm$2 SE). In 1992 the estimated annual average biomass increased to 17.0 $\pm$ 10.3 kg/m^2 (mean $\pm$ 2 SE), and in 1993 to ca 19.5 $\pm$ 7.8 kg/m^2 (mean $\pm$ 2 SE).

Table 6 show the biomass estimated from the dredge sampling in all four tidal areas in the Danish Wadden Sea. An average biomass figure from Grey, Knude, and Lister Deeps is used, to estimate the standing stock of mussels in Juvre Deep. The catch efficiency of the dredge is assumed to be 100% in the biomass estimations. The biomass in the four different tidal areas varied between ca 1.6 kg/m^2 (in Grey Deep South of Esbjerg) and 14.2 kg/m^2 (in Ho Bight North of Esbjerg, in the fishing sectors) (Tab. 6).

4.4. Estimations of the standing stock.

Estimates of the standing stock is achieved by multiplying the monthly average biomass (kg/m2) for each fishing sector, with the estimated area (in m^2) of each fishing sector determined from the aeroplane pictures, in Hjerting Stream. The estimations are shown in Table 3.

The standing stock estimations are based on biomass estimations from between 1 and 16 observations in the different sectors in Ho Bight (not all sampling stations were visited at each survey). Monthly figures from the surveyed fishing sectors are used in the none surveyed fishing sectors to estimate the biomass of mussels in those sectors (Tab. 3).

The estimations of the standing stock are only valid if the sampling stations are randomly distributed within the mussel beds detected from the aerial photos. This is the case for the subtidal mussel beds. However, the assumption of randomized sampling can not be validated for the intertidal beds. The coverage of mussels within beds in the intertidal mussel beds varied between 5 and 100%. In average 65% of the beds were covered with mussels (65 ±36%; mean ±2 SE; n = 25) from 1991-1993.To compensate for the coverage of mussels an average coverage figure of 0.65 was used in the estimate of the biomass in the intertidal mussel beds, although zero sampling stations was observed. Consequently, the standing stock in September 1993 may be reduced, from totally 93 296 metric tonnes to totally 76 753 metric tonnes in all three sectors in Hjerting Stream (Tab. 3).

In all three sectors an increase in the standing stock was observed from 1991 to 1993. In sector 1, the standing stock increased, as a year average, from 8 600 metric tonnes in 1991, to 42 000 metric tonnes in 1992, and to 48 500 metric tonnes in 1993 (Tab. 3). The annual standing stock was in 1993 10 700 metric tonnes in sector 2, and 7 000 metric tonnes in sector 3 (Tab. 3).

Estimations of the mussel stocks in the three fishing sectors in Hjerting Stream (exclusive Hobo Deep) based on the dredge surveys in September 1994, and with an assumed catch efficiency of 100%, indicate a standing stock of mussels of 56 857 ±23 100 metric tonnes (mean ±2 SE) (Tab. 6).

The standing stock of mussels in the entire Danish Wadden Sea was estimated to 116 879 ± 54 894 metric tonnes (mean ±2 SE) in September 1994 (Tab. 6).

5. Fishing of mussels, 1991-1994.

In 1991 and 1992 the annual gross catches in the two fishing sectors (1 and 2) were respectively 6 905 metric tonnes and 6 344 metric tonnes. The net catches were respectively 5 539 metric tonnes and 5 040 metric tonnes (Tab. 4).

A chance in the regulation in 1993, resulted in a smaller gross catch of only 5 031 metric tonnes, and a net catch of only 3 267 metric tonnes (Tab. 4), which only was 60% of the annual net catches in 1991 and 1992. In 1994 the gross catches increased compared to the catches in 1993, with ca 1 337 metric tonnes to 6 368 metric tonnes (Tab. 4). The net catches in 1994 were 4 635 metric tonnes, or 42% higher than in 1993.

The largest exploitation of the standing stock was in 1991, when 29% of the stock in Hjerting Stream (sector 1, 2 and 3 combined) was fished (Tab. 4). The average exploitation of the standing stock in 1992 amounted to only 8% in all three sectors, and in 1993 only 5%.

The annual average exploitation rate from 1991 to 1994 was 11% of the standing stock in all three sectors.

The exploitation rate from 1991 - 1994 did not result in a reduction in the standing stock of mussels in Hjerting Stream. Contrary, the standing stock increased more then 3 times, from 16 000 metric tonnes in May 1991 to 57 000 metric tonnes in September 1994.

When an average production index (P/B) of 0.4 (Asmus, 1987) for both sub- and intertidal mussel beds are used (cohort 1987), the standing stock in 1994 of 117 000 metric tonnes in the entire Danish Wadden Sea produced around 36 500 metric tonnes of mussels. This is eight times the amount of mussels fished (13% of P_{1994}) in 1994, which leaves 16 000 metric tonnes of mussels for the birds (44% of P_{1994}).

6. Estimates of bird predation of mussels in Danish Wadden Sea.

An accessible biomass of mussels of 16 000 metric tonnes wet weight gives 1 440 metric tonnes of AFDW (9% the wet weight) of mussel meat for birds to feed on in 1994 (Tab. 5).

An oystercatcher has a daily demand of consumption energy of 38 g AFDW of mussel meat (see chapter 3.4). This gives a potential number of oystercatchers, which may be sustained by the mussel production of $38 \star 10^6$ bird days, or more then 100 000 oystercatchers per day.

If eiders were the only mussel consuming bird species in the Wadden Sea, there would be food enough for $11.6 \star 10^6$ eider days. Eiders have, a daily energy need, which is more then three times as high as for the oystercatcher, or 124 g AFDW of mussel meat. The number of eiders which daily can nourish on mussels may be 32 000.

Herring gulls feed on the intertidal mussel beds. They have a daily consumption energy need of 90 g of AFDW of mussel meat, which gives $16 \star 10^6$ bird days annually for herring gulls. The daily number of herring gulls are 44 000 individuals.

The figures above are based on the assumption that the birds live on mussels alone, which is not the case. Additional, all three species are present simultaneously in the Wadden Sea. A separation in the feeding niche can be observed comparing eiders, oystercatchers and herring gulls reducing the competition for mussels.

The ornithologists have counted the number of all three species of birds in the Danish Wadden Sea. The latest counts observed, as a monthly mean, 19 500 oystercatchers, and 22 411 eiders (only from August to March=8 month). The counts of herring gulls observed 13 428 individuals (Laursen et al, 1994 and DAFNA, 1993).

If, the oystercatcher had to nourish on mussels alone, a consumption of 270 metric tonnes of AFDW of mussel meat could be expected annually, equal to 3 005 metric tonnes of live mussels (assumption: 9% of mussels are AFDW of meat). The eider stock (both sedentary and migratory eiders) could consume (in 245 days/year) 681 metric tonnes of AFDW of mussel meat, which is equal to 7 565 metric tonnes of live mussels. The herring gulls could consume 441 metric tonnes of AFDW of mussel meat, equal to 4 901 metric tonnes of live mussels (Tab. 5). If all three species of birds were living on mussels alone, they could consume 15 471 metric tonnes of live mussels.

Based on these calculations, the TAC=F=10 000 metric tonnes is an appropriate amount of mussels to be fished in 1995, leaving enough food in form of mussels for birds in the Danish Wadden Sea, and without a decrease in the size of the standing stock (B).

7. Discussion and conclusions.

Not all mussel beds were photographed in 1991 in 1993. However, all beds important for the fishery have been photographed in both years. The observed chances in the areas between 1991 and 1993 are based on the mussel beds important for the fishery, detected on the photos...

The subtidal areas with mussels in the three fishing sectors increased from 1991 to 1993 by 82%. Additional, the intertidal area decreased by 33%. It is difficult, to interpret, if the fishing had positive or negative impact on the size and distribution of beds in the fishing sectors. Other factors, such as predation from different species of birds and invertebrates, and ice winter destruction of especially the intertidal mussel beds, may be important too.

The large variation in density of mussels observed at the sampling stations, reflects the variation in number of mussels in place and time, caused by variation in the fishery intensity and variation in predation and settling of new spat. Spat fall was observed during the three years of investigation. However, they "disappeared" shortly after settlement. The densities of mussels can very considerably even within relatively small areas. Laursen and Egerrup (1992) found densities of mussels between 80 and 180 per square (20x20 cm) within an area of 2 m^2, which is equivalent to 2 000 and 4 500 mussels per m^2. Their finding is in accordance with the densities found in this investigation.

The dredge survey technique of the mussel stock (swept area) is just as useful, as using a diver, sampling the mussels within a frame, and assessing the coverage proportion of mussels at each sampling station. There are sources of errors using both techniques.

Measuring the dredge length after four seconds of dredging introduce errors. No navigation system to day can record such small distances. The biomass determinations used in this investigation could be optimized weighing the gross catch instead of judging the weight.

The diver introduce errors in the determination of the coverage proportion, which is assessed at each sampling station. The sampling has to be random, which may be difficult, when sampling in the intertidal mussel beds. There is always a certain chance of being subjective, when taking samples on scattered and exposed intertidal mussel beds.

The dredge survey technique is preferable, because it is less time consuming and less expensive, compared to survey and sampling by use of a diver. Both techniques have although, the same degree of precision.

From 1983-1987 the fishermen landed 85 000 metric tonnes, or calculated as annual average 17 000 metric tonnes, caught in the entire Danish Wadden Sea (no limitations on areas or on TAC were enforced at that time). If the birds only fed on mussels, they would have eaten an estimated amount mussels of 75 000 metric tonnes in the same period of time (1983-1987). Fishermen and birds have respectively fished and consumed (eliminated) 160 000 metric tonnes, or annually 32 000 metric tonnes. ½ of the stock for the fishermen (F) and ½ for the birds (M) ($Z=M+F >> P$). The result was a collapse in the fishable stock of mussels between 1988 and 1990. However, the 87-cohort of mussels settling in the autumn 1987 (15 500 tonnes; Munksgaard 1989) could provide sufficient food for eiders, herring gulls and oytercatchers in the Danish Wadden Sea.

The mussel fishery is often criticized for eliminating the food supply for mussel eating birds like eiders, oystercatchers, and herring gulls. Although, the estimations in this paper reveal, that the determined regulation of the Danish mussel fishery (ca 11% of standing stock as annual average), which has been implemented since 1990, has resulted in an increase of the standing stock of mussels in the fishing areas in Hjerting Stream from 16 000 metric tonnes in May 1991 (Tab. 3) to more than 57 000 metric tonnes in September 1994 (Tab. 6). The annual production of mussels has obviously been larger than the fishery mortality (F), the mortality by predation (M_P), and the natural mortality (M_N) by other courses than predation ($P > F + M$ ($M = M_P + M_N$)).

It is not in this investigation possible to analyse, whether the fishery and bird predation, at the present level, have positive or negative impact on the mussel stocks in the Danish Wadden Sea. Anyhow, the standing stock of mussels has increased more then three times between 1991 and 1994. Most of the intertidal mussel beds have survived due to no appearance of severe ice winters since 1986/87.

The regulation of the mussel fishery for 1995 in the Danish Wadden Sea has resulted in a TAC=10 000 metric tonnes, which is twice as high as the annual TAC for the last three years. A TAC_{1995} of 10 000 metric tonnes leaves 19 000 metric tonnes for the bird in 1995 (50% of the production P) before a reduction in the stock may occur. The regulation of the mussel fishery has therefore the last five years been carried out in agreement with a wise exploitation of the mussel stocks ($F = TAC <$ the annual P), and to secure sufficient food for the different bird stocks in the Wadden Sea.

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7. Tables and Figures.

Table 1. The areas (in km^2) of the mussel beds in each tidal area of the Danish Wadden Sea. The area in km^2 of each fishing sector 1, 2 and 3, and the fraction covered with mussel beds in Hjerting Stream are given as well.

Table 2. The average biomass (total wet weight) of mussels in kg/m2 of mussel bed. - : no sampling. (n): number of sampling stations.

Table 3. The estimated standing stock of mussels (in tonnes) in the three fishing sectors in Hjerting Stream, 1991-1993. ' X ': Figures between the apostrophes are extrapolated from the estimated monthly stock figures from the other monthly estimations each particular year. The estimations for the intertidal mussel beds have been corrected with a coverage factor of 0.65.

Table 4. Catches and stock of mussels in the three sectors in Hjerting Stream, 1991-1993, in tonnes. The annual average figures are from Table 3. The annual exploitation rates are given. ' X ': The areas in 1992 and 1994 are assumed equal to the areas the previous years (1991 and 1993 respectively). (*: Figures from Munksgaard, 1989).

Table 5. The annual food demands for oystercatchers, herring gulls and eiders in the Danish Wadden Sea in form of mussel meat. (*: Figures from Laursen et al, 1994 and DAFNA, 1993).

Table 6. Estimates of the mussel stock (in tonnes) after dredging in the four tidal areas of the Danish Wadden Sea in 1994.

Table 7. Estimates of P_{94} (production), F (fishery mortality) and M (mortality due to other causes than fishery and predation in 1994) on basis of the standing stock of mussels in 1994 (B_{94}). Three separate scenarios are given for F, 2xF and 3xF (F: The average annual net catch between 1991 and 1994).

Figure 1. The landings, VPA and TAC of mussels (*M. edulis L.*) in tonnes for the Danish Wadden Sea, 1979-1995. The figures from 1995 only covers the 1. half year of 1995.

Figure 2. The investigation sector's 1, 2 and 3 in the gully, Hjerting Stream, in the Ho Bight. All sampling stations are shown.

Table 1.

Tidal areas	Areas with mussels in 1991 in km2		Area with mussels in 1993 in km2	
	intertidal	subtidal	intetidal	subtidal
Grey Deep	5,01	1,09	3,39	1,98
Knude Deep	0,94	0,64	0,99	0,5
Juvre Deep	2,69	none	0,96	none
Lister Deep	0,49	0,06	0,85	none
The Wadden Sea	9,13	1,79	6,19	2,48
Sector 1 (ca 8 km2)	2,56	0,22	2,03	1,04
Sector 2 (ca 2 km2)	0,49	0,6	none	0,46
Sector 3 (ca 7,3 km2)	none	0,27	none	0,48
Sector 1-3 (17,3 km2)	3,05	1,09	2,03	1,98

Table 2.

Area	1991			1992			1993	
	May	August	October	April	June	September	June	September
Sector 1 (17)	0,7 (4)	6,8 (12)	6,2 (11)	19,0 (14)		25,1 (13)	18,5 (16)	22,6 (16)
Sector 2 (4)	18,7 (4)	–	9,1 (1)	–	29,3 (2)	26,1 (4)	13,5 (4)	33,1 (4)
Sector 3 (11)	6,8 (6)	1,4 (8)	–	6,0 (8)	7,6 (6)	–	10,9 (7)	18,1 (5)

Table 3.

Area	1991			1992			1993	
	May	August	October	April	June	September	June	September
Sector 1	1946	18904	17236	52820	'61299'	69778	56795	69382
Sector 2	20383	'15151'	9919	'30193'	31937	28449	6210	15226
Sector 3	1836	378	'1157'	1620	2052	'1826'	5232	8668
Sector 1-3	24155	'34433'	'28312'	'84633'	'95288'	'100063'	68229	93296
The standing stock figures below has been corrected with a coverage factor of 0,65 for the intertidal mussel beds								
Sector 1-3	15701	'22381'	'18403'	'55011'	'61937'	'65041'	56140	76753
Year average	'18828'			'60663'			66 447	

Table 4.

	1988	1991	1992	1993	1994
Area (km2) with mussels	1,7*	4,1	'4,1'	4,01	'4,01'
The stock in sector 1-3 in tonnes	15500*	18828	60663	66447	56857
Fished amount in tonnes:					
Gross (logbook data)	2560	6905	6344	5031	6368
Net (account data)	1161	5539	5040	3267	4635
Exploitation rates %	7	29	8	5	8

Table 5.

Bird species	Annual bird days*	Mussel meat demand (100%) tonnes of AFDW	Mussel meat demand (100%) tonnes wet weight
Oystercatcher	7117500	270	3005
Herring gull	4901220	441	4901
Eider	5490695	681	7565
All species	17509415	1392	15471
Food (P-1994) available		1440	16000
Food (B-1994) available		10530	117000

Table 6.

Dredge samples taken in various mussel beds in the Danish Wadden Sea in Sept. 1994.

Ho Bight	Station number	Catch in kg	Dredge speed	Dredge time in sec.	Swept area m2	Sample unsorted kg	Sample sorted kg	*corr. factor sorted kg	Fraction whole mussels	Mussels kg/m2	mean biomass		total mussels in tonnes
North	1	0	2	31	57,412	0	0	0	0	0			
of	2	250	2	14	25,928	3,42	2,81	3,372	0,985964912	9,508758256			
Esbjerg	3	0	2	20	37,04	0	0	0	0	0			
	4	350	2	12	22,224	3,34	2,65	3,18	0,952095808	14,99430944			
	5	0	2	11	20,372	0	0	0	0	0			
area	6	400	2	6	11,112	3,41	2,76	3,312	0,971260997	34,98259889			
in km2	7	0	2	22	40,744	0	0	0	0	0			
	8	200	2	13	24,076	2,42	2,18	2,376	0,981818182	8,155990877			
4,01	9	200	2	18	33,336	3,11	2,45	2,94	0,945337621	5,671571998			
	10	600	2	11	20,372	3,51	2,45	2,94	0,837606838	24,68935512			
	11	300	2	32	59,264	3,5	1,38	1,656	0,473142857	2,395094107			
	12	500	2	19	35,188	4,12	3,25	3,9	0,946601942	13,45083575			
	13	125	2	9	16,668	3,19	2,13	2,556	0,801253918	6,00892375			
plus	14	100	2	33	61,116	1,29	0,99	1,188	0,920930233	1,506856196			
Hobo	16	250	2	58	107,416	3,52	1,97	2,364	0,671590909	1,563060892		SI	
Deep	17	600	2	13	24,076	3,47	2,63	3,156	0,909510086	22,66597657	14,17891982	5,70068721	
total	18	500	2	12	22,224	3,73	2,15	2,58	0,691689008	15,58175774			
in km2	19	125	2	25	46,3	2,97	1,68	2,016	0,678787879	1,832580666			
1,30	42	600	2	13	24,076	3,54	2,06	2,472	0,698305085	17,40251914			
	43	450	2	17	31,484	3,69	2,67	3,204	0,868292683	12,41048492			
	44	250	2	16	29,632	2,98	1,71	2,052	0,688590604	5,80951846			
5,37	45	400	2	45	83,34	3,11	0,565	0,678	0,218006431	1,04634716			
	46	400	2	8	14,816	3,27	2,2	2,64	0,80733945	21,79642142			
	47	600	2	5	9,26	3,33	2,55	3,06	0,918918919	59,54118265			
	48	600	2	11	20,372	3,47	2,47	2,964	0,854178674	25,157432			
	49	400	2	28	51,856	3,45	2,27	2,724	0,789565217	6,090444441			
	50	600	2	9	16,668	3,98	3,1	3,72	0,934673367	33,64554956			
	51	500	2	4	7,408	2,99	2,26	2,712	0,907023411	61,21918273			
	52	0	2	14	25,928	0	0	0	0	0			
	53	300	2	10	18,52	3,36	1,43	1,716	0,510714286	8,272909596			
	54	500	2	10	18,52	4,55	3,4	4,08	0,896703297	24,20905229			
											Mean:	76140,79942	76141
											Max.:	107075,5851	107076
											Min.:	45206,01376	45206

*Correction for los of water by unfreezing samples ca 20%

Table 6. (cont.)

	Station	Catch	Dredge	Dredge	Swept	Sample	Sample	Corr. factor	Fraction	Mussels	mean		total mussels
Grey Deep	number	in kg	speed	time in sec.	area m2	unsorted kg	sorted kg	sorted kg	whole mussels	kg/m2	biomass		in tonnes
South	21	200	2	14	25,928	3,35	1,98	2,376	0,709253731	5,470948252			
of	22	0	2	17	31,484	0	0	0	0	0			
Esbjerg	23	400	2	20	37,04	3,14	1,89	2,268	0,722292994	7,800140032			
	24	0	2	15	27,78	0	0	0	0	0			
weal	25	300	2	21	38,892	3,77	2,97	3,564	0,94535809	7,292179036			
i km2	26	0	2	156	288,912	0	0	0	0	0			
	27	0	2	50	92,6	0	0	0	0	0		SE	
0,463	28	100	2	68	125,936	2,02	0,555	0,666	0,32970297	0,261802003	1,577002833	1,268783172	
	29	0	2	75	138,9	0	0	0	0	0			
	30	400	2	117	216,684	3,45	1,435	1,722	0,499130435	0,92139786			
	31	0	2	63	116,676	0	0	0	0	0			
	32	200	2	36	66,672	2,99	2,5	3	1,003344482	3,009792661			
	33	0	2	94	174,088	0	0	0	0	0			
	34	300	2	21	38,892	3,87	3,43	4,116	1,063565891	8,203994643			
	35	0	2	64	118,528	0	0	0	0	0			
	36	50	2	159	294,468	2,3	1,77	2,124	0,923478261	0,156804519			
	37	0	2	88	162,976	0	0	0		0			
	38	0	2	67	124,084	0	0	0		0			
	39	0	2	44	81,488	0	0	0		0			
	40	0	2	49	90,748	0	0	0		0			
	41	0	2	40	74,08	0	0	0		0			
											Mean:	730,1523117	730
											Max.:	1317,59892	1318
											Min.:	142,7057031	143

Knude	71	250	2	9	16,668	2,0983	1,788	2,1456	0,795167328	11,92655579			
Deep	72	500	2	10	18,52	2,848	1,997	2,3964	0,841432584	22,71686243			
	73	300	2	10	18,52	2,7334	1,712	2,0544	0,751591425	12,17480709		SE	
area	74	600	2	13	24,076	3,484	2,371	2,8452	0,816647532	20,35174111	14,44587196	5,842511592	
in km2	75	200	2	11	20,372	3,353	2,252	2,7024	0,805964808	7,912470022			
	76	200	2	13	24,076	3,447	2,59	3,108	0,901653612	7,49008157			
1,49	77	200	2	19	35,188	3,316	1,608	1,9296	0,581905911	3,30741111			
	78	300	2	9	16,668	2,374	1,417	1,7004	0,716259478	12,89163927			
	79	500	2	7	12,964	3,711	2,505	3,006	0,810024252	31,24129328			
											Mean	21524,34923	21524
											Max.:	30229,6915	30230
											Min.:	12819,00695	12819

Table 6. (cont.)

	Station number	Catch in kg	Dredge speed	Dredge time in sec.	Swept area m2	Sample unsorted kg	Sample sorted kg	*cor. factor sorted kg	Fraction whole mussels	Mussels kg/m2	mean biomass		total mussels in tonnes
Lister	55	0	2	24	44,448	0	0	0	0	0			
Deep	56	0	2	13	24,076	0	0	0	0	0			
	57	600	2	15	27,78	4,59	3,59	4,308	0,938562092	20,27131947			
	58	600	2	27	50,004	2,99	2,14	2,568	0,858862876	10,30553007			
area	59	0	2	21	38,892	0	0	0	0	0		SL	
in km2	60	0	2	46	85,192	0	0	0	0	0	9,769970504	8,225587288	
	61	250	2	23	42,596	3	2,07	2,484	0,828	4,859611231			
0,91	62	600	2	10	18,52	3,91	3,36	4,032	1,031202046	33,40827303			
	63	600	2	23	42,596	3,54	2,34	2,808	0,793220339	11,17316857			
	64	400	2	10	18,52	4,03	3,01	3,612	0,896277916	19,35805433			
	65	600	2	18	33,336	3,91	2,95	3,54	0,905370844	16,29537156			
	66	300	2	23	42,596	1,94	0,36	0,432	0,222680412	1,568319178			
											Mean	8890,673159	8891
											Max.:	14555,93939	14556
											Min..	3225,406927	3225

Juvre Deep	There has not been dredge for mussels in Juvre Deep in 1994 The average biomass from the other areas has been used to estimated the standing stock in Juvre Deep			
Area km2 0,96		9,99294128	9593,223628	9593

			st
Total	Mean in tonnes	116879	45894
	Max.:	162773	
	Min.:	70986	

NB! The estimates assumes a catch efficiency of the dredge of 100%.

Total area of mussel beds in the Danish Wadden Sea in 1994: 9,19 km2

Table 7.

Intertidal:			**Subtidal:**					
	km2			km2				
Area	6,56		Area	2,62				
						Standing		
B:	83430,49 tonnes			33321,325 tonnes		stock	Total tonnes	116879 tonnes
	P/B (Asmus, 1987)			P/B (Asmus, 1987)				sum	%
	0,2	16686,099 tonnes		0,6	19992,79521 tonnes	P: (mean)		36679

F + M = ? based on P

Fishery exploitation based on P:

Scenario 1	(The situation in 1994)	F	4263	11
		M (incl. predation)	32416	89
Scenario 2	(Prognosis 1)	2*F (1994 level)	8526	22
		M (incl. predation)	28153	78
Scenario 3	(Prognosis 2)	3*F (1994 level)	12789	33
		M (incl. predation)	23890	67

Fishery exploitation based on B:

Baseret på B: 116879

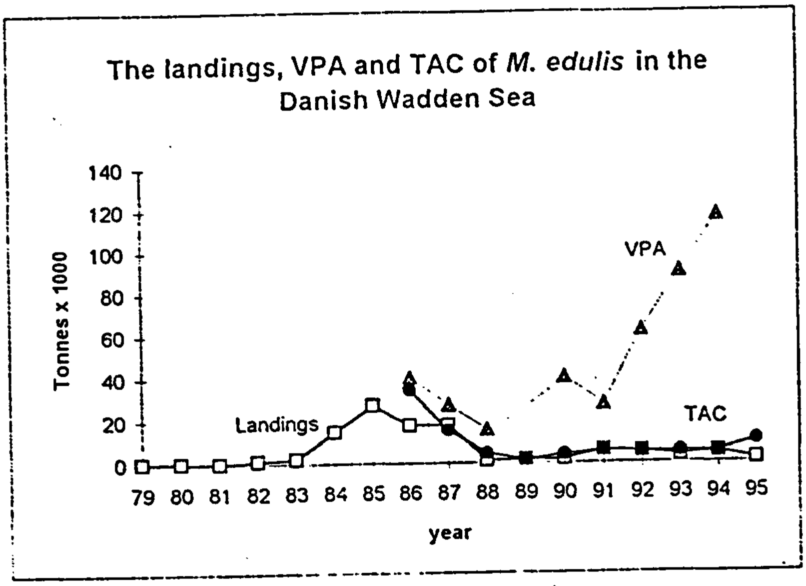
Scenario 1	F	4263	4
	M (incl. predation)	< 113000	96
Scenario 2	2*F	8526	7
	red. P + M	< 108000	93
Scenario 3	3*F	12789	11
	red. P + M	< 104000	89

Estimates (bird days living on mussels alone)
(based on the annual production of mussels)

Asumsion 84 g AFDW/bird/day, similar to ca. 1.0 kg wet weight of mussels)
Bird = an average food demand of an oystercatcher, a herring gull and an eider per day.

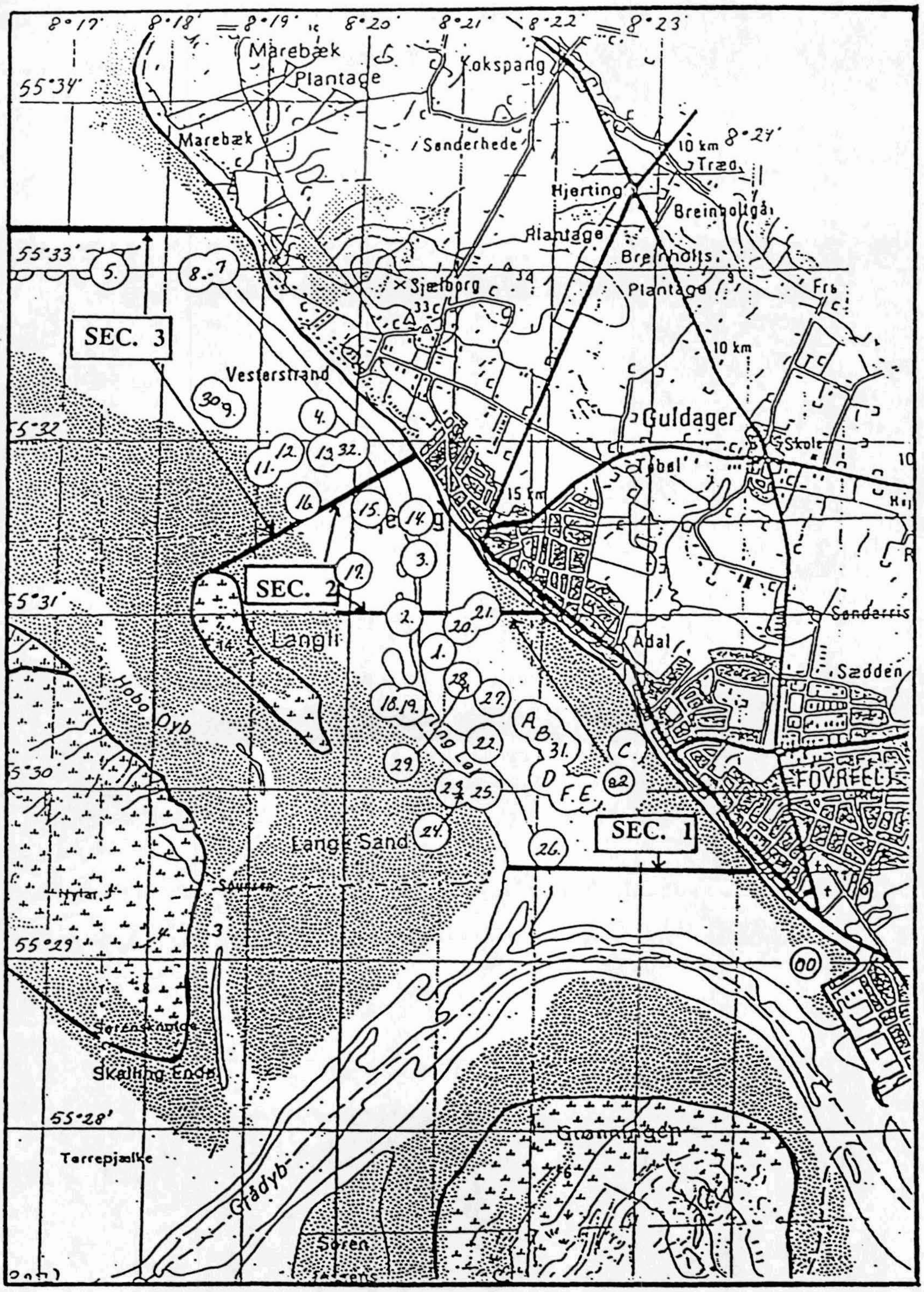
Scenario 1:	
50% of M = 16208	AFDW (8%) = 1297 tonnes gives ca 15.4 mill. bird days
Scenario 2:	
50% af P+M = 14076	AFDW (8%) = 1126 tonnes gives ca 13.4mill. bird days
Scenario 3:	
50% af P+M = 11945	AFDW (8%) = 956 tonnes gives ca 11.4 mill. bird days

Figure 1



The landings, VPA and TAC of M. edulis in the Danish Wadden Sea
140
120
100
80
60
40
20
0
Tonnes x 1000
VPA
TAC
Landings
79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
year

Figure 2.


8°17'
8°18'
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55°29'
55°28'
Marebæk Plantage
Marebæk
Kokspang
Sønderhede
10 km
Træa
Hjerting
Breinholtgå
Plantage
Breinholts
Plantage
Sjælborg
SEC. 3
Vesterstrand
Guldager
Skole
Tobøl
15 km
SEC. 2
Langli
Sønderris
Ådal
Sædden
Hobo Dyb
FOVRFELT
SEC. 1
Lange Sand
Skallingen Ende
Tørrepjælke
Grådyb
Søren