Report Number
670

Desk study to assess the impact of cockle suction dredging on The Wash and North Norfolk Coast European Marine Site

English Nature Research Reports

working today
for nature tomorrow

English Nature Research Reports

Number 670

Desk study to assess the impact of cockle suction dredging on The Wash and North Norfolk Coast European Marine Site

Michael C Bell & Peter Walker

The Centre for Environment, Fisheries & Aquaculture Science
Lowestoft Laboratory
Pakefield Road
Lowestoft
Suffolk
NR32 5DH

CEFAS
The Centre for Environment, Fisheries & Aquaculture Science

October 2005
CEFAS Contract No. C2252

ISSN 0967-876X

Cover note

Project officer	Conor Donnelly, Eastern Area Team conor.donnelly@english-nature.org.uk
Contractor(s) (where appropriate)	Michael C Bell & Peter Walker The Centre for Environment, Fisheries & Aquaculture Science Lowestoft Laboratory Pakefield Road Lowestoft Suffolk NR32 5DH

The views in this report are those of the author(s) and do not necessarily represent those of English Nature

This report should be cited as:
BELL, C.M., & WALKER, P. 2005. Desk study to assess the impact of cockle suction dredging on The Wash and North Norfolk Coast European Marine Site. *English Nature Research Reports*, No 670.

Acknowledgements

We would like to thank everyone who contributed to the production of this report, in particular Ron Jessop, Matt Mander and Judith Stoutt of Eastern Sea Fisheries Joint Committee, Mike Bailey and Penny Coad of Ecomaris, Joss Wiggins of Kent & Essex Sea Fisheries Committee and Mick Yates of CEH.

Executive summary

- The Wash is designated for its nature conservation importance under EU Birds and Habitats Directives. The designations reflect the importance of the extensive intertidal and subtidal habitats and their importance for shorebirds during the winter and on passage. The Wash also supports a major fishery for cockles, prosecuted mainly by suction dredging in intertidal areas. Concern about conflicts between mechanised fishing and nature conservation have led to the closure of suction dredge fisheries for cockles in the Wadden Sea. This report examines the potential for suction dredging to affect features of conservation interest in The Wash, and considers how the potential impacts could be mitigated by fishery management.

- Suction dredging has been the main method of harvesting cockles in The Wash since the late 1980s, superseding the earlier method of 'blowing' using the draught from ships' propellers. Early dredges used in the Thames Estuary used the Venturi principle to generate the hydraulic lift, but Wash dredges have always used solids handling pumps based on Dutch modifications to the early dredge design. Solids handling pumps are thought to give superior performance, particularly in terms of the damage to cockles in the dredge pipes. The report reviews the general design features and their variation in Wash cockle dredges.

- Each stage of the dredging process is reviewed in detail, assessing the overall contribution to damage and mortality of cockles in both the retained and discarded portions of the catch. Cockles rejected at the onboard riddle suffer additional mortality of 10-20% compared with undisturbed cockles, provided that they are undamaged. Damage rates of 10% or less are possible under good practice. Mortality of damaged cockles is effectively 100%. Much less is understood about damage and mortality of cockles rejected at the dredge head, which is potentially an important part of the overall impact. Limited experimental data suggest that the additional mortality is likely to be around 50% higher than that inflicted at the riddle. Overall, it is estimated that additional mortality of undersized cockles passing through the dredge is 27%.

- Direct fishing mortality, ie removal of commercial cockles by the fishery, is the largest part of the overall impact of suction dredging on the target organism. Harvest rates are uncertain, but are likely to have exceeded those in the Thames Estuary (35%) over recent years.

- There is circumstantial evidence that suction dredging does not adversely affect settlement of juvenile cockles in The Wash. This is in contrast with findings in the Dutch Wadden Sea, where dredge-induced loss of fine sediments has caused declines in recruitment of several bivalve species.

- Survival of cockle spat over the first year is lower in The Wash than in other areas of the UK. There is no evidence to link this effect with suction dredging, but limited evidence from other sites suggests that there is potential for this to occur. Suction dredging does appear to cause 20-30% additional mortality of pre-recruit (undersized) cockles in areas where dredging occurs. There may be some potential for this mortality to be partially compensated by decreases in other mortality sources.

- There appears to be little potential for suction dredging to cause population level consequences by disturbance of spawning activities. The summer fishing season occurs once cockles have regained condition following spawning. Cockle settlement success in The Wash is determined by environmental factors rather than supply of larvae.

- We conclude that the principal impact of suction dredging on cockles is through damage and mortality of undersized cockles rejected at the dredge head and the onboard riddle. The significance of the additional mortality to the stock as a whole depends on the extent to which undersized cockles co-occur with commercial cockles in the areas targeted by dredgers.

- Cockles co-occur with other benthic invertebrate species in nine out of ten separately identified intertidal biotope types in The Wash. The most important biotopes types are "polychaetes and *Cerastoderma edule* in fine sand or muddy sand shores" (MNCR biotope code LMS.Pcer) and "dense *Lanice conchilega* in tide-swept lower shore sand" (MNCR biotope code LGS.Lan).

- Crustaceans are the most important predators of newly settled cockle spat, and the most important of these are brown shrimp (*Crangon crangon*) and shore crab (*Carcinus maenas*). There is no evidence that their abundance in The Wash is ever limited by the availability of cockles.

- Shorebirds are the most important predators of post-settlement cockles. Knot (*Calidris canutus*) and oystercatcher (*Haematopus ostralegus*) are specialist bivalve predators that are present in Internationally Important numbers (>1% of the flyway population) in The Wash. Declines in knot numbers in The Wash appear not to be linked with the availability of cockles, but there is potential for suction dredging to affect the abundance of other potential prey items, notably the bivalve *Macoma balthica*. For oystercatcher, there is evidence of increased annual mortality in years when both cockle and mussel stocks are low in The Wash. Oystercatcher predation precedes the fishery in terms of direct mortality of cockles, but there is potential for suction dredging to affect the availability of undersized cockles. The impact of suction dredging on the supply of cockles to oystercatchers will depend on the relative spatial distributions of commercial and undersized cockles.

- Studies at other sites indicate that suction dredging may cause loss of fine particles from sediments, with consequences for sediment stability and benthic community structure. The vulnerability of sediments and benthic communities appears to be directly related to the amount of shelter. The greatest impacts are observed in areas of fine sediment in sheltered areas. Eelgrass beds are particularly susceptible to disturbance by suction dredging. Coarser sediments in more exposed areas are naturally dynamic, as are the communities they support, and are relatively quick to recover following dredging. Commercial cockle fishing in The Wash occurs mainly (but not exclusively) in areas of relatively coarse sediment. These areas may be relatively robust to potential dredging impacts compared with other sites such as the Wadden Sea. In some years, suction dredging occurs in more sheltered, muddier areas of The Wash where impacts may be greater and recovery times longer. Biotopes with a 'structural' element (*Lanice* tubes) in the sandy areas may also be more vulnerable to dredging, but these are thought to be relatively unimportant in terms of commercial cockle concentrations.

- Hand-gathering is the least damaging method of fishing for cockles, particularly in terms of damage to undersized cockles. Impacts on benthic communities are likely to be slight because of the restricted spatial scale of operations. 'Blowing' of cockles using the draught from ships' propellers, practised extensively in The Wash prior to the advent of suction dredging, appears to be less damaging to undersized cockles than suction dredging, but the impact on benthic environments and communities is probably substantial. Impacts on cockles and non-target benthos are at least as great for tractor dredging as for suction dredging. Initial damage to cockles appears to be lower after tractor dredging, but this does not appear to be realised in terms of lower indirect fishing mortality. As for suction dredging, benthic impacts appear to be greater, and recovery times longer, in muddy than in sandy sediments.

- The report reviews aspects of dredge design and operation that are relevant to the mitigation of impacts on cockles, non-target benthos and sediments. Many of these aspects, such as pump design, are under constant review by fishermen and gear technologists. More information is needed on selection and damage to cockles at the dredge head.

- Fishery management has a strong role to play in the mitigation of impacts. Traditionally this has involved setting harvest levels and minimum legal sizes. Spatial management may be particularly important in limiting fishing activities to areas of minimum impact on both target and non-target species. Technical measures, such as limits on breakage and discard rates, may also be very effective in minimising the impact of fishing outside of the direct harvest of commercial cockles.

- The biota and environment of much of The Wash appear to be naturally dynamic and therefore fast to recover from the impacts of suction dredging and other perturbations. Overall, we conclude that suction dredging for cockles in The Wash need not be incompatible with maintaining the features of the site that are of nature conservation importance. However, there are important caveats to this conclusion concerning the vulnerability of certain areas of The Wash, and impacts on non-target biota, such as *Macoma*, with implications for important overwintering bird populations. There is considerable scope to manage the fishery to mitigate any impacts of suction dredging.

- The report makes a comprehensive list of future research needs. These include research aimed at improving our understanding of the dredging process, particularly rejection of undersized cockles at the dredge head, and experimental field studies with a rigorous Before-After-Control-Impact design, aimed at estimating *in situ* impacts on cockle populations, non-target benthos and sediment.

- A large amount of data is already available on the fishing activities, environment and biota of The Wash. The report briefly reviews the available data resources and makes recommendations for further monitoring and future analyses based on existing data. In particular, there is a need to compile data on fishing activities, bird numbers, benthic invertebrates and sediments according to a common framework of spatial reference. This would make it possible to test hypotheses about links between fishing activities and trends in environmental and biotic factors in The Wash.

Contents

1 Introduction

The Wash has supported an important fishery for cockles (*Cerastoderma edule*) for more than a century (Dare and others 2004). The Wash is also notable for its nature conservation importance. It is classified as a Special Protection Area (SPA) under the EU Birds Directive and designated as a Special Area of Conservation (SAC) under the EU Habitats Directive. The designations reflect the importance of the extensive intertidal and subtidal habitats of The Wash and their importance for shorebirds during the winter and on passage. English Nature has a duty to advise government and relevant bodies on activities likely to damage or disturb these features of nature conservation interest.

Suction dredging has been the main method of fishing for cockles in The Wash since the late 1980s (Dare and others 2004). A recent evaluation of the Dutch shellfishery policy in the Wadden Sea and Oosterschelde (EVA II) has concluded that suction dredging for cockles in these areas has damaged the sediment and benthos and contributed to declines in shorebirds (Ens and others 2004b). On the basis of this evaluation, the Dutch government has ruled that suction dredging in the Wadden Sea is not sufficiently sustainable or compatible with the aim of promoting ecologically sustainable economic development. The fishery was prohibited with effect from 1 January 2005. Closures of Danish and German cockle fisheries in the Wadden Sea were already agreed at the 6th Trilateral Government Conference on the Protection of the Wadden Sea (1991 at Esbjerg), which highlighted the negative ecological effects caused by fishing for cockles. In 1994 cockle fishing was banned in all except a small area of the Danish Wadden Sea (Kristensen, 1994; Dahl and others 1997). The inception of three national parks covering the entire German Wadden Sea in 1985, 1986 and 1990 drastically reduced the area available to cockle fishing (Seaman & Ruth, 1997). Following concerns about the mortality of benthic organisms, the fishery was banned in Schleswig-Holstein in 1989 and in Lower Saxony in 1992, although according to Seaman & Ruth (1997) this was largely for political reasons.

Despite the reasons for closure of these fisheries in the Wadden Sea, it does not automatically follow that suction dredging for cockles in The Wash is incompatible with the nature conservation features of the site. This report reviews the available evidence on the nature of impacts of cockle dredging on the cockles themselves, their environment and the organisms with which they share living space. We describe the relevance of these studies to The Wash, identify gaps in our knowledge which will require future research, and consider ways in which any impacts of suction dredging can be mitigated by managing and modifying the fishing activities. We also briefly review the available data on cockle fisheries and stocks and the environment and biota of The Wash which may allow further analysis of the possible impacts of suction dredging.

2 Suction dredging gear

2.1 Development and uptake of suction dredges for cockles in the UK

Hydraulic dredges have been used to harvest molluscs around the world since the 1940s (Coen, 1995). However, it was not until 1966 that the first trials of mechanical dredging methods for cockles were attempted in the UK (WFA, 1967). Up to this time, practically all harvesting of cockles was by hand gathering. In response to a perceived need to improve both the working conditions of fishermen and the productivity of the fisheries, in 1966 the White Fish Authority (WFA) in conjunction with the Severnside Oyster Company (Bangor) Ltd designed and developed a continuous lift system for cockle dredging (WFA, 1968).

Improving on the mechanical elevator design used since the early 1950s by Canadian clam dredgers (eg Adkins and others 1983), this early dredge used suction generated by the Venturi principle to deliver cockles from the dredge to the fishing vessel (WFA, 1967). Sediment and cockles were fluidised by water jets mounted at the front of the dredge (digging jets) and directed by a blade into an enclosed chamber. Water jets were used to wash out sediment and undersized cockles, whilst a powerful water jet directed up a large diameter pipe provided the suction to lift cockles up the pipe onto a sorting screen mounted on the side of the vessel. Size selection of cockles was achieved both on this screen and on the mesh of the dredge itself. The harvest rate of cockles per man hour taken by this method was estimated to be 6 to 20 times greater than by hand gathering (WFA, 1967), although this has to be set against the increased processing time needed to separate the marketable catch from empty shell and broken cockles (Franklin & Pickett, 1972).

Figure 2.1 illustrates the dredge and its deployment. Although there have been design modifications to the dredge head and the pipework, and solids handling pumps are now used to generate suction in preference to jet hydraulic pumping systems, modern suction dredges used to harvest cockles in The Wash and the Thames Estuary are very similar to these early dredges. The first trials were undertaken with a 0.61 m (2 ft) wide dredge at Aber Sands, North Wales and in the River Towy Estuary in South Wales, and then with a 0.3 m (1 ft) dredge (suitable for the smaller vessels) in the Thames Estuary (WFA, 1968). These trials were used to fine-tune the gear design and method of operation (depth, towing speed, towing chain length, water pressure), and to establish that the fishing method was commercially viable in terms of productivity and the quality of the processed product.

The Thames Estuary was a suitable area for the introduction of this fishing method, since unlike other major cockle fishing areas in Britain there were no restrictive bye-laws on methods of fishing. Following the success of the 1966 and 1967 trials, a year's commercial trial with a 0.3 m dredge in the Thames was completed in 1968, and by the end of 1969 there were six commercial vessels fishing 0.46 m (1 ft 6 ins) dredges (Franklin 1972). The last vessel operated by hand gatherers in the Thames ceased operation in 1971, by which time nine suction dredgers were working (Franklin & Pickett, 1972). One of these vessels was operating a 0.61 m dredge (Pickett, 1973), and in 1972 Kent & Essex Sea Fisheries Committee (K&ESFC) introduced a bye-law restricting the blade width of dredges to no more than this size (2 ft). However, by the late 1980s it was reported that vessels were using 0.61 m blades in dredges with a larger aperture, effectively increasing the operational width to 0.76 m (J. Wiggins, in litt.). This width was set as the limit for dredge aperture and blade in a new bye-law by K&ESFC in 1992. By the end of the 1990s, the number of local vessels licensed to use suction dredges within the area of the Thames Estuary Cockle Fishery Order had increased to 14, but this was supplemented by variable numbers of visiting vessels from the Wash fishery, fishing outside the Fishery Order area. The maximum number of vessels in any one year was 32 in 1996, which included 20 visiting vessels (J. Wiggins, unpublished data).

The dredge developed by the WFA in the 1960s and subsequent improvements to this jet pump design up to the late 1980s are described in detail by Siddle (1988). The original static sorting screen had by this time been replaced by a motorised rotary riddle. A more important development, however, rendered this jet pump dredge design obsolete within a few years. In modifying the original WFA design for use in the Wadden Sea cockle fishery, Dutch engineers pioneered the replacement of the jet pump with a solids handling pump to generate the suction, and modified the dredge head to allow most of the digging to be performed by a high velocity water jet rather than the dredge blade (Johnson, 1988). The potential was soon recognised in Britain for this technology to reduce damage to undersized cockles and to reduce the amount of sand and grit in the meats during processing. A solids pump dredge suitable for British cockle vessels was developed by the Sea Fish Industry Authority in 1988. Trials in The Wash showed that increased catch rates and reduced damage rates were achieved compared with the WFA dredge (Johnson, 1988). In 1991 all vessels fishing in the Thames Estuary had converted to using the solids pump dredges.

This new dredge technology was adopted in the Wash cockle fishery soon after the inception of hydraulic suction dredging at the site. Four vessels started using the WFA dredge in the Le Strange private fishery in 1986, and a bye-law introduced in 1987 allowed suction dredging in The Wash generally (ESFJC Annual Reports). By 1988, 19 of the 37 vessels in the fishery were using suction dredges. This method of fishing was rapidly superseding the earlier method of 'blowing', whereby vessels use the draught from their propellers to concentrate cockles for subsequent hand gathering. In 1989 only four vessels were blowing, and by 1993 less than 1% of the cockle landings from The Wash were taken by this method. Most if not all vessels were using the more refined solids pump dredges by the end of the 1980s, allowing relatively high catch rates even at a time when stock levels were decreasing. The catching capacity of the Wash fleet by this time exceeded available cockle stocks (Dare and others 2004). Variable numbers of dredgers operated in The Wash during the 1990s, with many vessels switching their attentions to the Thames fishery. In 2003, there were a total of 36 cockle dredgers in the Wash cockle fleet, 18 operating from each of King's Lynn and Boston. Almost half of these vessels also fished in the Thames Estuary (outside the area of Fishery Order) during the year. Details of the dredges currently used in the Wash fishery are given in Section 2.2.

Use of cockle suction dredges in the UK is largely limited to the Wash and Thames fisheries. The Burry Inlet fishery is restricted to hand gathering. Most landings from North Wales and the north-west of England are also taken by hand, although mechanical dredges towed by tractors have also been used in the past (see Rees, 1996). Suction dredges have been used briefly in Traeth Lafan, North Wales, and there are anecdotal accounts of suction dredging having occurred in the Camel Estuary, Cornwall. Suction dredging contributed to the intensive fishing of cockles in the Solway Firth in the late 1980s and early 1990s, but was banned in 1992 (tractor dredging was banned in 1994) following stock declines and poor recruitment (Davis and others 2004). Recent years have seen limited use of suction dredges on the English side of the Firth, primarily to establish a track record of fishing prior to the introduction of a Regulating Order.

Outside of the UK, suction dredges for cockles have mainly been used in the Wadden Sea and Oosterschelde fisheries. The Dutch cockle fisheries introduced mechanical dredges in the 1950s, but these were 'batch' dredges that needed to be lifted to be emptied on board (Ens and others 2004b). A continuous lift system based on the WFA design was introduced into the Dutch fisheries in the late 1970s. As described above, solids handling pumps were used to provide the lift rather than a Venturi jet – a design modification that was soon to be adopted in the UK (Johnson, 1988).

2.2 Current dredge design in The Wash

Suction dredges used to fish for cockles in The Wash follow the general design of the solids pump dredges described above, but there is great variability in the details of their construction. A general description is given here, with some of the possible variations.

Dredge head

Only one dredge per vessel is permitted under the terms of the Wash Fishery Order 1992. The maximum width of blade and aperture is 0.76 m. Most dredges in use are of this width, although some may have openings as small as 0.62 m. Company owned boats use dredge heads of a design based on recent Dutch expertise, but fabricated by the company's own engineers. Independent operators either make their own dredge heads or have them manufactured locally.

Dredge heads are equipped with straight movable blades which can penetrate the sea bed to a depth of about 5 cm. Many dredge heads now incorporate an entry door to aid the removal of blockages in the pipework. Sections of rubber pipe can be fitted onto dredge head bars to reduce the width of spaces between the bars and hence decrease the minimum size of cockle retained.

Pipework

The pipe up which the cockles are lifted from the dredge head to the onboard riddle can be either flexible or solid. Flexible pipework is an earlier design feature, now used mainly by older, smaller vessels although some have converted to solid pipes. Solid pipes are said to be easier and safer to use, as blockages are less common. However, flexible pipes appear to be able to operate in slightly deeper water.

Pumps

Solids handling pumps used as part of suction dredge gear by cockle vessels in The Wash have varied widely in size (4-10 ins pipe diameter) and manufacturer. However, concerns over recent years about damage rates of cockles passing through the pumps have led to a number of manufacturers falling out of favour. Damage presumably arises from excessive abrasion and knocking against impellor vanes and the pump casing. At present, the larger sizes of pump from only two manufacturers are used by the majority of Wash vessels. This is an aspect of gear specification that is likely to continue to evolve as new pumps become available and are tested by fishermen.

Riddles

Various riddle designs are illustrated in Figure 2.2. The early design of stationary sorting screen has never been used in The Wash. Outboard mounted rotary riddles with longitudinal bars of mild steel are still found on some older vessels. Newer (larger) vessels have deck-mounted fore and aft riddles made from stainless steel bars. Riddles made from a series of stainless steel rings have been used, but at present two-section riddles with both longitudinal bars and rings are widely used.

The same design of riddle can be used for both cockles and mussels, the bar spacing being varied by the addition of various sizes of tubes over the bars. Detailed design changes have been evolved to reduce impact damage to cockles leaving the delivery pipe and entering the riddle. Some vessels, for example, deliver the cockles down rubber-protected chutes into the riddle. Buffer tanks (wash boxes), used during mussel dredging to rinse the catch before riddling, are not generally used whilst dredging for cockles

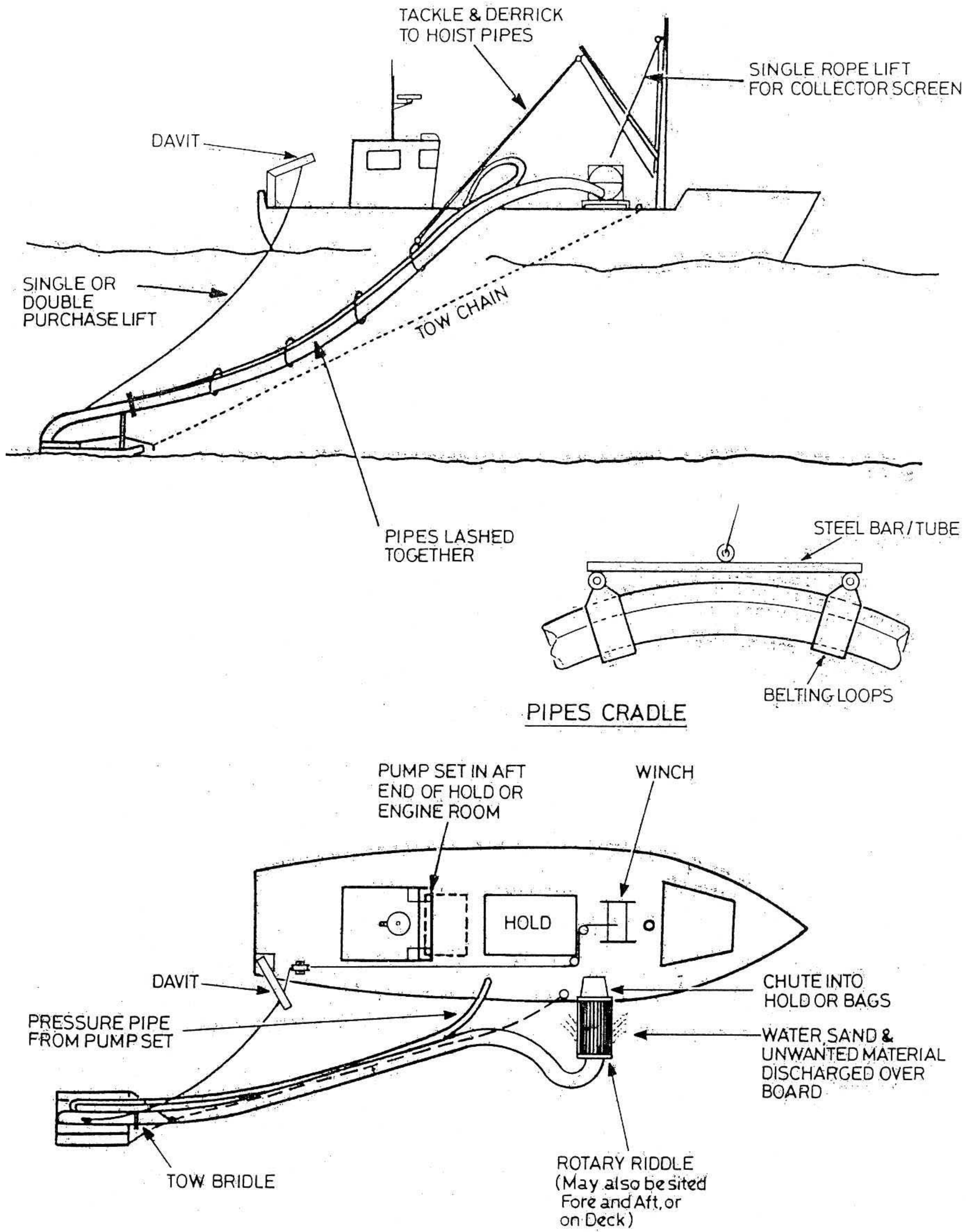
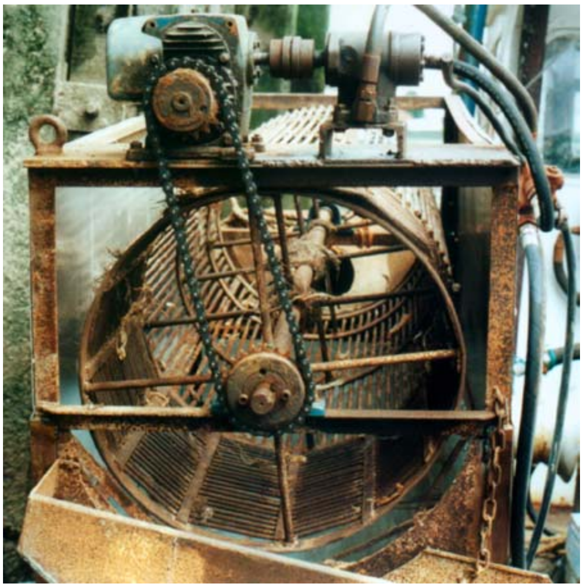


Figure 2.1 Suction dredge gear and its deployment. Diagram taken from Siddle (1988).

(a)



(b)

Figure 2.2 Designs of riddles currently used in the Wash suction dredge fishery for cockles: (a) older style, outboard operated riddle in stowed position (note section nearest camera made of a series of rings, further section made from longitudinal bars); (b) newer style of fixed, fore and aft mounted riddle showing longitudinal bars. Photographs courtesy of ESFJC.

3 Impacts of suction dredging on cockles

The most obvious and direct impacts of cockle suction dredging are on the target species itself. Much effort has been expended during the development of dredges and deployment protocols to minimise damage to cockles in the catch and thus maximise the quality of the product supplied to processors. These developments are also relevant to impacts on discarded cockles and, indeed, other benthic fauna. Conclusions from earlier studies about suction dredging impacts thus need to be treated with caution in assessing their relevance to current dredging practices in The Wash.

Impacts on cockles differ according to stages of the dredging process (Figure 3.1) and between cockle life-history stages (Figure 3.2). Each of these stages is considered separately below, and Table 3.1 gives an overall assessment of the importance of each component of the overall impact.

3.1 Components of the dredging process

Blade impact

Impact from the blade mounted at the front of the dredge is the first opportunity for dredging to kill or damage cockles. According to Pickett (1973), increased breakage of cockles can result from setting the dredge blade at too shallow an angle. In early development trials, it was also found that when towing at too high a speed (>1.5 knots) the forward edge of the dredge rose up, causing the blade to act as a guillotine for cockles in its path (WFA, 1968). Under these conditions up to half of the cockles in the dredge track were damaged, compared with 3% or less when the dredges were operated correctly. These results apply to the original Venturi lift dredges, where part of the function of the blade was to cut into the sand. In modern dredges, where the lift is provided instead by solids handling pumps, the purpose of the blade is mainly to guide cockles into the dredge head rather than to penetrate the substrate, the latter function being provided mostly by the high pressure digging jets directed forward of the dredge blade. The impact of the digging jets on cockles and other benthic invertebrates is unknown, but assumed to be small, although it is possible that they contribute to the loss of fine particles from the sediment in some circumstances (Section 4.4). There may also be some potential for damage to soft-bodied invertebrates such as polychaetes. Blades are now not universally fitted to dredges. There are no quantitative data available, but it is reasonable to infer that blade impact is a relatively small component of the overall mortality and damage to cockles inflicted by modern suction dredges.

Dredge track

In common with almost all fishing gear, cockle suction dredges are not 100% efficient as sampling devices. In other words, there are cockles within the track of the dredge that are neither rejected during the dredging process nor appear as part of the retained catch. In addition to blade impact described above, mortality and damage among these cockles might occur from contact with the dredge head or simply from disturbance after the passage of the dredge. The early WFA trials with a 30 cm dredge in the Thames Estuary suggested that typically 80% of cockles in the dredge track were harvested (WFA, 1968). However, the remaining 20% included undersized cockles, many of which will have been rejected at the dredge head. Only a single cockle (out of an unknown but large total number) was found to be damaged in the dredge track. Cook (1991) examined damage rates in the dredge track after experimental fishing with a suction dredger in Traeth Lafan, North Wales. Two observations showed cockle density in the dredge tracks to be 8.5% and 19% (14% for the two samples combined) of that in the immediately adjacent areas, with zero and 21% respectively (14% for the two samples combined) of these remaining cockles in the dredge track being damaged. However, this is likely to have included individuals damaged during blade impact as well as rejects, particularly from the dredge head. Modern dredgers are likely to be relatively efficient in extracting all size classes into the dredge, and so we assume that the potential for damage and disturbance to unharvested cockles in the dredge track is relatively small compared with the damage and disturbance within the dredge itself.

Rejection at dredge head

Much of the sorting and rejection of undersized cockles in a suction dredge occurs at the dredge head. Rejection at the dredge head is thus likely to be an important factor in the overall mortality and damaged caused to undersized cockles by dredging. To our knowledge, the only study that has specifically addressed this aspect of the dredging process was by Wiggins (1991) in the Thames Estuary. Sections of a suction dredge head (16-18 mm grill size) were covered with 12 mm square wire net. After 8 minutes fishing, a total of 74 live cockles had collected in the mesh, mostly from the rear rather than the side of the dredge head. Six cockles (8%) were obviously damaged and were considered beyond hope of survival. After 7 days in an aquarium the total mortality had increased to 16% and after 41 days (6 weeks) to 50%. Unfortunately, no control sample was available, so it is impossible to say how much of the mortality was due to rejection at the dredge head *per se* and how much to the aquarium conditions. However, much more is known about mortality of rejects from the riddle (see below), and so a parallel experiment with riddle rejects can provide a preliminary indication of how the two mortality sources compare. Out of a sample of 107 cockles taken from the reject side of the onboard riddle during the same period of fishing, 7 (7%) were obviously damaged. Mortality in the aquarium had increased to 10% after 7 days and 36% after 41 days.

Since these experiments are the only available source of information on the relative importance of rejection at the dredge head as a component of fishing mortality during suction dredging, the data from Wiggins (1991) bear closer examination. Figure 3.3 shows cumulative mortality of riddle and dredge head rejects during almost six weeks in the aquarium. Initial mortality from obvious damage was similar in the two samples, statistically indistinguishable according to 95% confidence intervals. By 16 days, mortality was much higher in the dredge head rejects, and in both samples the mortality continued to increase along parallel trends for the rest of the experiment. The ratio between dredge head mortality and riddle mortality is an informative quantity because it potentially can be used to assess the likely levels of dredge head mortality to compare with riddle mortality from other dredging trials. Figure 3.4 shows that during the first two weeks the mortality rate was much higher in the dredge head rejects, but by 4-6 weeks the ratio settled down to about 40-50% higher mortality in dredge head rejects than in the riddle rejects. The most important values of the ratio are: (i) 1.24 (0.36 to 3.98, 95% CI) for initial damage rates; (ii) 1.41 (1.00 to 1.99) for the mortality of all cockles over the longer term; and (iii) 1.47 (0.98 to 2.21) for the mortality of cockles without shell damage.

The conclusion from this analysis is that, whilst initial breakage rates of cockles may be fairly similar between rejection at the dredge head and rejection at the riddle, mortality over the longer term may be 40-50% higher in the dredge head rejects. The dredge used in these Thames trials was of the standard modern type, fitted with a solids handling pump system and rotary riddle. The results could thus be taken to be applicable to the dredges currently used in The Wash. However, a single set of experiments, with small sample sizes and without a statistical control sample, is a very slender basis for conclusions about the importance of rejection at the dredge head as a source of mortality and damage to undersized cockles. It is also worth noting that fishing gear properties are notoriously specific to individual vessels and individual operators.

Given the ESFJC proposals to introduce upper limits for the rejection rate of cockles at the riddle on suction dredgers, it is absolutely vital that an improved understanding be gained, firstly of how much size selection is actually achieved at the dredge head rather than the riddle, and secondly of the contribution of rejection at the dredge head to the overall indirect fishing mortality of cockles inflicted by suction dredging. The intended effect of the discard limit is to reduce the indirect (unseen) element of fishing mortality, ie to ensure that most of the cockles killed by suction dredging are counted against the landings quota. Two types of response to such a limit could be envisaged. In the first place, vessels may restrict their operations to areas dominated by large (commercial) cockles, thereby minimising the number of undersized cockles encountered by the dredge. Under this scenario, reduced discarding (and mortality) at the riddle implies reduced rejection (and mortality) at the dredge head, thereby achieving the ends of the management measure. Alternatively, fishermen may seek to improve the size-selection at the dredge head, thereby minimising the number of undersized cockles that enter the riddle. Given the possibility that rejection at the dredge head inflicts greater mortality than rejection at the riddle, under this scenario the effect of the discard limit would be actually to increase the indirect fishing mortality. Whilst the second scenario is perhaps the less likely response, it is clear that more data on mortality at the dredge head is needed for a full understanding of the potential effects of management. It is recommended that future studies be undertaken into (i) the size-selection properties of dredge heads in modern suction dredging gear in The Wash, and (ii) the levels of mortality inflicted after rejection in these dredge heads.

Travel up pipe

Pickett (1973) cited abrasion in the pipe as an important potential source of damage to cockles taken during suction dredging operations. According to Rees (1996), much of the damage to cockles in the early Venturi lift dredges occurred because of the high velocities at which cockles struck the Venturi jet and bends in the pipes. In laboratory studies Franklin & Pickett (1978) found higher mortality in cockles taken by suction dredging (40% over 10 days) than in cockles taken by blowing (5% over 10 days). Hydraulically dredged cockles were also in poor physiological condition (low rates of siphon extrusion and pumping) compared with blown and hand-raked cockles. They attributed these differences to the effects of buffeting in the dredge delivery pipe, although rejection at the riddle may also have been a contributing factor.

Conclusions about the Venturi lift dredges cannot be taken to apply to modern solids handling pump dredges. In developing the solids pump dredges for use by UK cockle dredgers, the WFA undertook comparative trials with Venturi and solids pump dredges (Johnson, 1988). During fishing in The Wash, two vessels recorded 11% and 9% of cockles in the retained catch as being damaged whilst fishing with solids handling pumps, compared with 40% and 50% respectively whilst fishing with Venturi dredges. For the dredgers currently operating in The Wash it is generally considered that cockle damage rates are lower in dredges fitted with solid pipework than in dredges with flexible pipes, perhaps because the latter are more prone to blockages. There are no quantitative data to support this conclusion, however. In practice, damage from this source is not separable from damage recorded at the riddle (see below).

Passage through pump

As noted above, the introduction of solids handling pumps caused a four- to five-fold decrease in the amount of damage to retained cockles compared with the earlier Venturi design. Most of this reduction in damage is likely to be due to reduced buffeting in the delivery pipe. The extent to which passage through the pump contributes to the remaining impact is unclear. We are not aware of quantitative data on cockle damage or mortality caused specifically by this element of the dredging process, but concerns about damage from the pump have certainly caused fishermen to experiment with different pump specifications. A variety of pump specifications are currently used by fishermen in The Wash (see Section 2.2). These differ mainly in size and manufacturer. This is probably one of the least constant elements of dredge gear design, as fishermen will test new pumps as they become available. In the original WFA development trials with solids handling pumps, Johnson (1988) noted damage rates in the catch varying between 2.5% and 38%, with notable differences according to the type and operating speed of the pump.

As with travel up the delivery pipe, the impact of passage through the pump must be considered as part of the overall damage and mortality recorded in the retained catch and among riddle rejects.

Rejection at riddle

Discarding at the riddle is certainly the best studied part of the dredging process. However, as noted above, it is not possible to separate the effects of riddling *per se* from the effects of other processes that occur once the cockles are lifted up the delivery pipe. Damaged cockles in both retained and rejected portions of the catch at the riddle may have incurred the damage at any stage of the dredging process. Early studies with Venturi dredges (eg Franklin & Pickett, 1978) may be omitted from further consideration here, as the buffeting in the delivery pipe and sorting on a static screen are not representative of the processes in a modern suction dredge.

The results of dredging trials undertaken by Wiggins (1991) in the Thames Estuary have already been summarised above in considering the effects of rejection at the dredge head. This study found 7% of cockles rejected at the riddle to be damaged, and of those cockles without obvious external signs of damage 31% failed to survive for more than six weeks (Figure 3.3). These results were obtained after fishing with a solids pump dredge fitted with a rotary riddle, so presumably are relevant to modern suction dredging operations. However, the continually increasing trend of mortality over the course of time in the aquarium (Figure 3.3) and the absence of a control sample to account for the effects of aquarium conditions make the results difficult to interpret in terms of additional mortality inflicted by dredging.

What the Thames study does highlight, however, is that it is essential to distinguish between cockles that are immediately and obviously damaged – chipped and smashed shells – and those that appear intact but which nevertheless suffer additional mortality as a result of having passed through a suction dredge. Cockle damage rates at the riddle appear to be quite variable between operators, but the 7% recorded by Wiggins (1991) is very much on the low side. Cook (1991) recorded damage rates of 11-14% in riddle rejects during experimental suction dredging at Traeth Lafan, and this may be more typical of modern suction dredges. Mander and others (1999) commented that smash rates recorded in the catch of Wash cockle dredgers were as high as 50%, and it may be presumed that damage rates can be similarly high in the riddle rejects. During relaying trials in The Wash, Mander & Trundle (2000) noted an average damage rate of 11% (range 3-23%) in mainly two year-old cockles taken by suction dredging. Distinction was made between chipped and smashed cockles, with the former slightly predominating, but it was later found that even slightly damaged cockles did not survive two months after relaying.

Damage rates during suction dredging for cockles in the Thames Estuary are regularly assessed in order to enforce a maximum breakage rate of 10%. Some important work on cockle damage rates and mortality of discards has been undertaken recently by officers of ESFJC with a view to introducing and evaluating the same maximum breakage rate for cockle suction dredging within their district. ESFJC's bye-law 3 on methods of molluscan shellfishing (April 1997) specifies that fishing gear will not be granted a certificate of approval for operation within the Wash Fishery Order if more than 10% by weight of the target species is smashed. Breakage rate assessment was introduced to the Wash cockle fishery in 2001, with a protocol that involved measuring damage rates in the retained catch and discards combined (Mander & Trundle, 2001). The majority of the cockle fleet were able to achieve damage rates below the 10% threshold within two assessments, largely by fine-tuning the gear set-up. Following trials with the survival of damaged cockles in 2001 (Mander & Trundle, 2001, and see below), the definition of damage in these assessments was strengthened in 2002 to include cockles with any visible damage to the valves (Trundle & Jessop, 2002). Damage rate assessments were not completed during the 2002 fishing season, but about one in three of the dredging vessels reached the required standard upon first testing. In most of these assessments the damage was predominantly recorded in the retained catch, but this largely reflects the scarcity of undersized cockles on the fishing grounds at the time.

It is uncertain that damage rates are directly comparable between small and large cockles. Coffen-Smout (1998) noted that the umbo is weaker than the domed high point in larger cockles, whereas the margin and high point are relatively more weak in small cockles (see Figure 3.5). Cook (1991) recorded damage rates of 26% in one year-old cockles discarded at the riddle, compared with 6% of older cockles. However, it would probably be a mistake to conclude that damage rates are necessarily drastically higher in discards than the retained catch. In tractor dredging experiments (including use of a rotary riddle) in the Burry Inlet, Cotter and others (1993, 1997) found damage rates in dredged areas that were relatively similar between cockle age-classes (5-9%). For now we assume that damage rates in cockles rejected at the riddle of suction dredgers are at least as high as those in the retained catch.

Recent studies by ESFJC in The Wash provide a great deal of directly relevant information on the mortality of damaged and undamaged cockles discarded at the riddle of suction dredgers. Mander & Trundle (2000) reported on the survival of cockles taken by suction dredgers and subsequently relaid for on-growing. More than 60% of cockles reburied within two hours of relaying, those remaining on the surface being the larger and damaged individuals. Low level predation by gulls, oystercatchers and starfish removed the dead and dying individuals on the surface within a short period after relaying. Excluding the 13% of cockles that were already smashed, around half of the biomass of relaid cockles survived after two months. None of the damaged cockles were recorded among the survivors, not even those chipped individuals that successfully reburied. These results are indicative of the level of survival that may be expected amongst riddle rejects, but without replication or a control sample of undredged cockles it would be unwise to extrapolate this result to riddle discards directly. Fortunately, a series of aquarium and field experiments were undertaken in The Wash in 2001, the results of which provide a detailed quantitative appreciation of levels of mortality in dredge discards (Mander & Trundle, 2001). The study was undertaken using discards from the riddles of Wash cockle dredging vessels, and is thus directly relevant to current fishing operations in The Wash using modern suction dredging gear. An initial sample of riddle rejects, including cockles with varying levels of damage, showed 100% mortality over six days in an aquarium, compared with 10% mortality in a control (hand picked) sample (aquarium experiment 1). In subsequent experiments, cockles without external damage (undamaged) were considered separately from damaged cockles, and the damaged sample was restricted to 'chipped' individuals (shell hole <5 mm in diameter). Two aquarium experiments gave widely different results – over the course of 13 days experiment 2 showed 35% and 80% mortality respectively in undamaged and damaged discards, whereas experiment 3 showed 100% mortality in both groups within a week. Three experiments with cages on a natural cockle bed showed rather more consistent results, with 87% mortality of damaged discards and 28% mortality of undamaged discards within five weeks.

It is relevant to ask what these results mean in terms of additional mortality inflicted by suction dredging. There are two elements to this question: (i) what are the components of overall mortality that are added by damage and by the dredging process? and (ii) what would these added components have been if the experiments were allowed to continue indefinitely? In other words, it is necessary to find out what is the total **additional** mortality contributed by suction dredging. Using the data presented by Mander & Trundle (2001) we can calculate separate, additive components, allowing us to calculate mortality rates adjusted for control samples (ie aquarium or cage effects), and to isolate the effects of damage from the effects of the dredging process *per se* (see Appendix 1). The results of these analyses are presented in Figures 3.6-3.8. Excluding the results of aquarium experiment 3, which appear to be unrepresentative, additional mortality of undamaged dredged cockles was in the range 9-22% over five weeks (average 15%, cages 1-3) (Figure 3.6). After five weeks the mortality seemed still to be increasing relative to the control sample (the *x*-axis in Figure 3.6 effectively represents the control), but it is reasonable to suppose that most of the additional mortality might have occurred by this time. Damaged cockles showed 80-100% mortality (average 92%, cages 1-3) over five weeks, most of which occurred within five days (Figure 3.7). These figures are for mortality due solely to the damage, but given the greater importance of this component, adding in the effects of dredging makes only a very small increase to the overall mortality (average 93%, cages 1-3) (Figure 3.8).

It is important to note that the data of Mander & Trundle (2001) relate to the impact of a single passage through a dredge. On commercially fished beds it is likely that undersized cockles will be taken on more than one occasion as the vessels criss-cross the ground. This would probably increase the mortality of rejected cockles, and certainly increase the chances of shell damage. No data are available at a fine enough spatial scale to quantify this, however.

The recent ESFJC experiments provide the most up-to-date and relevant assessment of the levels of indirect fishing mortality inflicted by suction dredging of cockles. Cockles rejected at the riddle of suction dredges appear to suffer additional mortality of 10-20% compared with undisturbed cockles, provided that they are undamaged. As with damage rates (see above), there are some indications that cockle size should be taken into account. Jessop and others (2003) found that mortality in a dredge was more than twice as high in cockles >14 mm shell width than in smaller cockles. In practice, however, it is difficult to assess the effects of size-related differences in mortality without a more detailed analysis. The ESFJC experiments showed very high, but not necessarily 100% mortality of damaged cockles. Mander & Trundle (2001) showed that over the short-term mortality of damaged cockles in their experiments was related to the extent of damage – 50% over 5 days for a 1 mm diameter hole, 100% mortality over 5 days for holes of 6 mm and larger. Mortality could be higher than this under field conditions, however, not least because of increased exposure to predators resulting from the delayed reburrowing response (eg Coffen-Smout & Rees, 1999). Damage also extends the range of predators able to tackle cockles of any given size. Considering all the available data, including the results of the Wash relaying trials (Mander & Trundle, 2000), it seems safest to assume complete mortality of all damaged cockles.

Retained catch

Most of the impacts of suction dredging on cockles considered in this report come under the heading of indirect fishing mortality. It should be remembered, however, that the greatest single impact is likely to be **direct** fishing mortality, ie removal of cockles from the stock by the fishery. Incomplete data on abundance and low survey precision make it difficult to assess the exploitation rates of cockles in The Wash, but Dare and others (2004) considered that since the introduction of suction dredging the exploitation rate has in the past exceeded that in the Thames Estuary suction dredge fishery (around 35%). Consideration of damage rates in the retained catch is not appropriate here, since all retained cockles contribute to fishing mortality, irrespective of damage. Levels of direct fishing mortality would be influenced by minimum landings sizes imposed on the fishery. However, the current proposals for cockle fishery management in The Wash are to limit permitted discard rates, potentially transferring what is now indirect fishing mortality (among the discards) into direct fishing mortality, counted against any catch limits.

3.2 Vulnerability at different life-history stages

Settlement

Marine and estuarine invertebrate larvae are known to be highly sensitive to geochemical gradients within the surface layers of sediments, and may actively select against sediments that display geochemical profiles characteristic of disturbance (Woodin and others 1995, 1998, and see Section 4.4). It is pertinent to consider, therefore, whether suction dredging over cockle beds may create conditions that are adverse to settlement of cockle larvae. Based on the evidence of spatfall on commercially dredged areas in The Wash and Thames Estuary, the answer would appear to be that dredging does not have this adverse effect. As noted by Dare and others (2004), cockle spatfalls do occur on areas of The Wash that have been regularly suction dredged for 10 years or more. Several substantial settlements have been recorded on previously dredged grounds, as shown for recent years in Table 3.2. Dare and others (2004) showed that recent levels and variability of cockle spatfall in The Wash are unchanged compared with the historical period before suction dredging, and spat densities recorded in autumn surveys are comparable with other UK estuaries. Suction dredging has occurred for more than 35 years in the Thames Estuary without obvious effects on the distribution or abundance of spatfall. Franklin & Pickett (1978) showed that spatfall levels in experimentally dredged areas in the Thames Estuary were similar to those in adjacent, unfished areas, irrespective of whether the dredging was carried out in the autumn or spring before settlement. This was taken to indicate rapid recovery of dredged grounds once fishing had ceased, and Franklin & Pickett (1978) predicted that long-term recruitment to the cockle fishery would not be affected by suction dredging. These experiments were undertaken in 1969-71 using a Venturi rather than solids pump dredge, but there is no reason to suppose that the latter would be more damaging to settlement. Experimental areas were dredged intensively, "simulating the disturbance caused by commercial fishing operations over a wider area during many weeks". At Traeth Lafan, after experimental fishing with a solids pump dredge, Cook (1991) observed that dredged areas showed higher cockle spatfall than undredged areas, but noted that this was probably an effect of substrate suitability.

Whilst there is at least circumstantial evidence that suction dredging does not have a long-term negative effect on cockle spat settlement in The Wash and Thames Estuary, it is possible that this may not be true of all sites or all sediment types. Piersma and others (2001) presented evidence of effects on settlement of cockles and other bivalves in an area of the western Wadden Sea that was suction dredged in 1988. Low rates of cockle settlement were observed for a period of eight years after dredging. This was attributed to a loss of silts and a negative feedback process that prevented the re-accumulation of the fine sediments that are favourable to bivalve settlement (see Section 4.4 for more details). Previous studies in the Wadden Sea did not show a negative effect on cockle spatfall (de Vlas, 1987). More recently, studies under the EVA II programme have described generally lower densities of cockle spat in areas of the Wadden Sea open to fishing than in closed areas, although this pattern was reversed in the years 2001-2004, perhaps because of the negative effect on spatfall of high adult densities in the closed areas (Ens and others 2004b). Analyses under EVA II found a significant negative relationship between spatfall in the Wadden Sea measured in autumn and fishing effort one year earlier, but a similar effect was not detected in the Oosterschelde estuary (Kamermans and others 2003 cited by Ens and others 2004b). Hiddink (2003) found no effects of suction dredging on densities of spat and one year-old cockles in the Groninger Wad area of the Dutch Wadden Sea.

The Wash cockle fishery generally occurs during the summer months (June-September or October). Settlement of larvae is likely to commence in May, so the fishery will coincide with the period over which cockle spat are becoming established. Nevertheless, based on the evidence available we conclude that, although there may be negative effects of suction dredging on cockle spatfall in some areas, this probably is not true of The Wash. In recent years, known areas of significant cockle spatfall have usually been closed to fishing, and this is probably a sensible precaution. In Section 9.1, below, we suggest that the issue be examined more closely through detailed analysis of spatio-temporal patterns in fishing effort and spatfall.

Spat survival

Dare and others (2004) showed that survival of cockle spat over the first year, and particularly over the first-winter, is much lower in The Wash than in the Thames Estuary or Burry Inlet (Table 3.3). Although comparative data are not available for the period before the start of suction dredging in The Wash, it might seem reasonable to suppose that dredging may have caused high mortality of spat. However, given the relative survey and fishery timings, it seems unlikely that low spat survival is a direct consequence of fishing. Spatfall in The

Wash has generally been measured in September, **after** the main period of the fishery. Based on targeted surveys following the fate of individual cockle year-classes at Heacham during 1986-90 (see Dare and others 2004), it appears that most of the spat mortality occurs during the winter (Table 3.3), **before** the main fishery starts up again in the year following settlement. Indirect effects of suction dredging on spat survival cannot be ruled out (eg effects on sediment stability), but it seems unlikely that low spat survival is a direct consequence of damage and disturbance caused by passage through suction dredges. Other factors, such as predation by knot (see Section 4.3), are more likely to account for overwinter spat mortality in The Wash.

Suction dredge trials during 1969-71 in the Thames Estuary showed that the early Venturi dredges did appear to reduce survival of spat in this area (Franklin & Pickett, 1978). Commercial dredging at the time continued throughout the year. Compared with adjacent unfished areas, numbers of spat surviving to the October following settlement in fished areas were reduced by 50-75%, depending on the intensity of fishing. As already noted, damage and mortality of cockles in the Venturi dredges is likely to have been much greater than in modern solids pump dredges, so the results of this Thames study cannot be applied directly to current dredging operations in The Wash. However, after experimental fishing with a solids pump dredge in Traeth Lafan, Cook (1991) found that spat densities were reduced by 50%. Damage rates of 26% in recently settled cockles rejected at the riddle suggested that dredging is likely to have contributed substantially to this depletion.

We conclude that there is no proven effect of dredging on survival of cockle spat in The Wash, but based on limited evidence from other sites, there appears to be potential for this to occur.

Survival and growth of pre-recruits

The definition of 'pre-recruits' depends on the minimum commercial size in a fishery and the rate of growth in reaching this size. These vary between cockle stocks and fisheries, but in most cases pre-recruits, as distinct from spat, are predominantly cockles in their second year. Here, we define pre-recruits as being synonymous with undersized cockles. It is useful to distinguish the processes of spat settlement and survival, as in the preceding paragraphs, but the effects of fishing on older undersized cockles are also relevant to cockles in the first year of life.

In Section 3.1, results of various studies in The Wash and elsewhere were described showing that there is the potential for high mortality of undersized cockles rejected at the dredge head and at the riddle of suction dredges. Damage rates are very variable between operators, but levels of around 10% in riddle discards appear achievable under good practice. Damaged discards may survive over the short term, but are effectively lost to the stock and the fishery. Rejection at the riddle adds an additional 10-20% to total mortality of undersized cockles. Damage and additional mortality are probably at least as high amongst cockles rejected at the dredge head. A conservative estimate would be that in dredged areas, undersized cockles are likely to suffer mortality of 20-30% in addition to background (natural) mortality (10% damage during rejection at the dredge head plus 10-20% additional mortality of undamaged rejects). If we accept that the results of Wiggins (1991) are typical with respect to relative mortality of dredge head and riddle rejects, then additional mortality of undersized cockles may be even higher than this, depending on the relative contributions of the dredge head and the riddle to size selection[1]. Whatever the actual figures, it can be seen that suction dredging has the potential to reduce significantly the numbers of cockles recruiting to the adult stock. Comparing dredged and undredged areas in the Thames Estuary, Franklin & Pickett (1978) recorded 50-80% reduction in the number of second year cockles surviving to commercial size in dredged areas, depending on the intensity of fishing. Accounting for the difference in impact between Venturi dredges and modern solids pump dredges, this result suggests that our conclusion of a minimum of 20-30% additional mortality of undersized cockles is probably realistic (see also Section 3.3).

The mortality caused to undersized cockles by suction dredging is certainly 'additional' in the sense that cockles are killed that otherwise would have survived in at least the short-term. However, it is possible that over the longer-term this replaces other sources of mortality. Cook (1991) found that over an extensive area of Traeth Lafan, dredging appeared to cause no reduction in the densities of one year old cockles. It is hard to reconcile this result with damage rates of 26% recorded for one year old cockles rejected at the riddle during the same study. Based on stock survey data for the Burry Inlet, Bell and others (2001) described results that suggested that fishing and bird predation replaced other (unknown) sources of cockle mortality (see Section 4.6). It would be pure speculation to suggest that this might be true of cockles in The Wash, but if such compensatory mechanisms could be identified, this would have a very strong bearing on the development of Wash cockle management policy.

In addition to mortality of undersized cockles, it is also likely that the accumulated stress of repeated dredging will cause reduced growth of undersized cockles in fished areas. However, no quantitative data exist to support this assertion. The most direct consequence of reduced growth is that it represents foregone production for the stock and the fishery. Conceivably, it might also prolong the time taken for cockles to grow out of the size-classes that are most vulnerable to certain predators such as oystercatchers. Probably reduced growth has fairly minor consequences for cockle stocks compared with increased mortality, but it may in the future be important to test this assumption.

Finally, it is worth noting that recent survey data hints that suction dredging does indeed have an impact on densities of undersized cockles in The Wash (R. Jessop, pers. comm.). Part of the Holbeach bed was opened for fishing in 2004, and received intensive dredging from 28 vessels. Spring (pre-fishery) and autumn (post-fishery) surveys showed a 10% reduction in density of pre-recruit cockles after fishing, whereas densities remained constant on adjacent unfished areas. Given pre-recruit biomass increases of 64% in the fished area and 123% on the unfished area, this implies increases in average individual weight of 82% and 123% respectively. Survey precision is likely to have been low, and confirmation of these findings would require a full statistical analysis, but these results suggest that both survival and growth of undersized cockles were adversely affected by suction dredging on the Holbeach bed. Further studies of this kind are urgently needed to quantify the potential impacts on pre-recruit survival and growth in The Wash.

[1] Based on a confidence interval of 1-2.2 for the ratio of dredge head mortality to riddle mortality (see Section 3.1), the additional mortality to undersized cockles would be in the region of 20-42%, supposing that size selection was equally split between the riddle and dredge head. A worst case would be 20-54% if all sorting took place at the dredge head.

Survival of adults

It has already been noted that fishery removals are probably the most important source of additional mortality inflicted by dredging. As noted by Cook (1991), there may also be an unseen mortality of commercial sized cockles if dredging operations are inefficient (see comments about blade impact and the dredge track in Section 3.1). Although, as noted for pre-recruit cockles above, there may be some scope for fishing to replace other sources of mortality (Bell and others 2001), it is precautionary to assume that direct fishing mortality represents a net loss to the stock. Low survey precision and incomplete data make it difficult to assess the survival rates of adult cockles in The Wash, and these rates are probably very variable between years and individual cockle beds. It is safe to assume, nevertheless, that fishing mortality is a very important component of overall mortality of Wash cockles. This was certainly true during the 1990s, when cockles were dredged down to very low densities in some areas (Dare and others 2004). Dare and others (2004) pointed out that depletion of a stock to the point when each year's fishery is dependent on a single recruiting year-class has strong implications for the level and stability of stocks and fishery yields, particularly for a stock that exhibits very variable spatfall and low and variable survival to recruitment.

Spawning

There is a presumption that spawning cockles should not be disturbed by dredging. Spawning of cockles occurs from May to June or July, and occasionally as late as August (Boyden, 1971). Cockle spat can be detected in survey samples in The Wash as early as late May (P. Walker, pers. obs.). Cockles are in best commercial condition once they have had a chance to regain flesh weight following spawning, and the main cockle fishing season in The Wash is generally the summer (June-September or October). For this reason alone, disturbance to spawning cockles by dredging is probably minimal in The Wash.

If dredging were to occur during the peak spawning season it is doubtful that this would have much impact on the subsequent spatfall success. Settlement of cockles in The Wash appears not to be constrained by production of larvae, being determined instead by a combination of environmental factors (winter temperatures and wind-driven current systems in early summer) and a negative relationship with the density of the adult stock (Young and others 1996; Dare and others 2004). We conclude that disturbance to spawners probably is not an important impact of suction dredging on cockle stocks in The Wash.

3.3 Population level consequences of dredge impacts

This section briefly summarises the information described above on the importance of each stage of the dredging process and of each cockle life-history stage in the overall impact of suction dredging on cockles in The Wash. Table 3.1 provides an overview.

Suction dredging impacts on cockle stocks principally in terms of increased mortality. In addition to direct fishing mortality of the commercial stock, there is an indirect (hidden) component to fishing mortality caused by immediate damage and increased mortality in the short- to medium-term of cockles that encounter the dredge but do not form part of the retained catch. Depending on the efficiency of dredging operations, considered to be fairly high, there may be some additional mortality of commercial size cockles not lifted from the sediment by the dredge but impacted by the dredge head or blade.

The most important components of indirect mortality appear to be immediate damage and increased mortality of cockles discarded at the dredge head and the deck riddle (Table 3.1). This is likely to affect principally the survival and possibly growth of undersized cockles before recruitment to commercial size. There is a need for a better understanding about how much size-selection takes place at the dredge head compared with the riddle. Limited data suggest that mortality of dredge head rejects may be higher than that of riddle rejects, but this requires rigorous confirmation.

Several other components of indirect fishing mortality remain open to question (Table 3.1). Available data indicate that early life-history stages of cockles probably are not impacted heavily by suction dredging in The Wash, but conflicting evidence from elsewhere suggests that this issue should be studied further.

Table 3.4 shows how the total indirect fishing mortality inflicted on a cockle stock can be calculated, and indicates likely values for some of the parameters. Assuming size-selection equally split between the riddle and the dredge head, 10% damage to rejects at both stages, 15% additional mortality of undamaged riddle rejects and $1.5 \times 15\% = 22.5\%$ additional mortality of undamaged dredge head rejects, the additional mortality to undersized cockles passing through the dredge is 27%. This suggests that total mortality inflicted by the fishery could be 27% higher than the fishing mortality implied by any catch limit (this could in fact be an underestimate, since no account is taken of repeated dredging). Depending on the size-composition of the stock in the dredged areas, the indirect mortality potentially could exceed the direct fishing mortality in numerical terms (note that there is considerable potential for fishery management to limit this indirect component of fishing mortality by placing a limit on the allowed rate of discarding – see Section 6.3). Given the uncertainties involved in this type of calculation, arising not least from differences in the distributions of undersized and commercial cockles, it is recommended that indirect fishing mortality should be determined by comparison of pre- and post-fishery surveys between fished and unfished areas. This is unlikely to be practicable on a routine basis, but intensive surveys coupled with an experimental fishery could provide a useful calibration.

3.4 Applicability to current dredging operations in The Wash

Two themes have emerged in Sections 3.1 and 3.2. The first is that the ways in which dredging operations impact on cockles are very specific to particular dredge designs. For example, early dredges using the Venturi principle to lift cockles up the delivery pipe caused much more damage to both discards and retained cockles than modern dredges using solids handling pumps. Where possible, conclusions from studies of dredging impacts have been related to current dredging operations in The Wash. However, there are many subtle ways in which dredge design and operating protocols can evolve over time and thereby decrease the likely impacts. It is not clear, for example, that apparently modern solids pump dredges used 15 years ago in trials in the Thames Estuary or Traeth Lafan are directly comparable with dredges that may be used in The Wash in 2005. In the absence of firm evidence to the contrary, it is precautionary to assume that current dredging operations have at least as much impact as seen in earlier studies, but allowance should also be made for improvements in performance over time. The introduction of maximum breakage rates for cockles has shown that it is possible for operators to make improvements when required to do so. The introduction of maximum discard rates may have a similar effect. Whilst this report gathers together the available information on likely dredging impacts, it will be important to create a firm new baseline for the performance of the current Wash cockle fishery, and to monitor and document any future improvements.

The second theme to emerge, particularly from Section 3.2, is that some dredging impacts are very site-specific. For example, loss of fine-grained sediments after dredging appears to reduce settlement of cockles in at least part of the Wadden Sea, whereas in The Wash and the Thames Estuary there is circumstantial and experimental evidence that cockle settlement is not reduced after dredging. It would appear that some aspects of dredge impacts are dependent on the biological, hydrodynamic and sediment conditions at individual sites. Again, every effort has been made to draw conclusions that are specifically relevant to The Wash, but firm baseline data are needed to inform future management of the site.

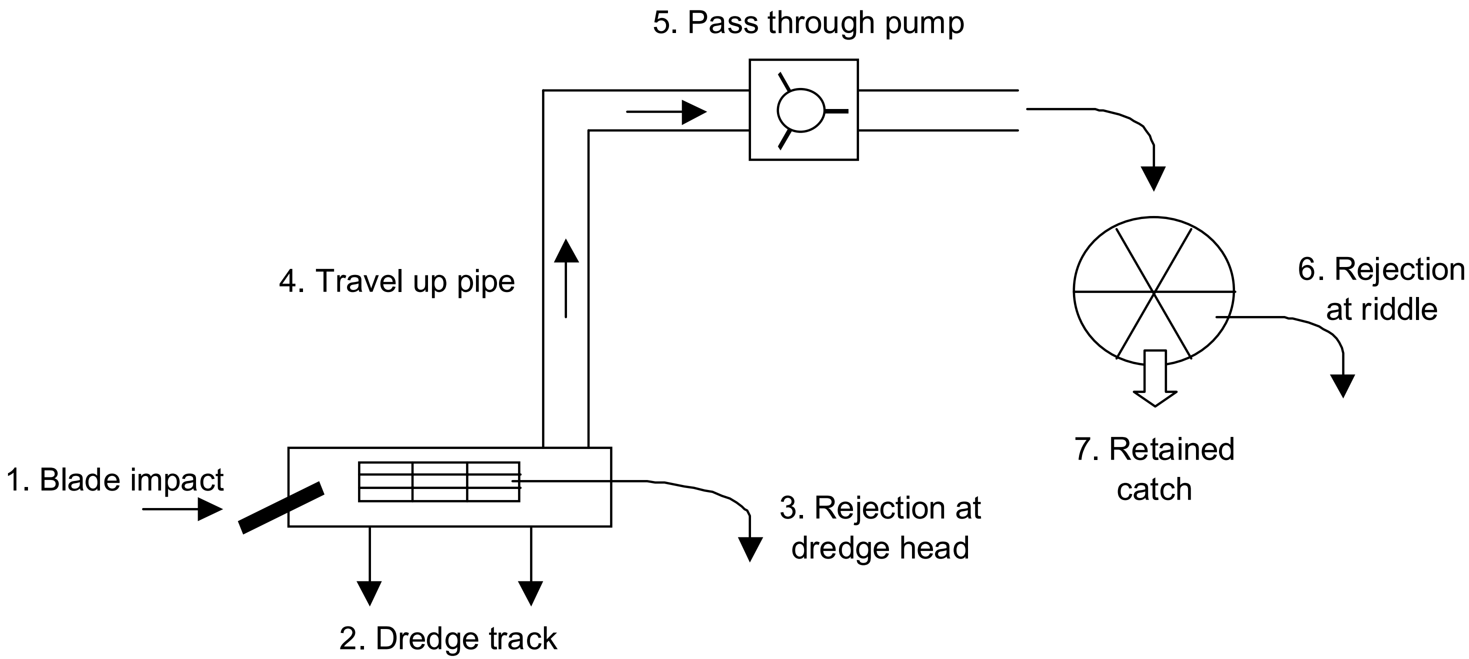


Figure 3.1 Schematic diagram of a cockle suction dredge, showing the critical points where the catching process could potentially affect the survival or condition of cockles. Numbers refer to impacts listed in Table 3.1.

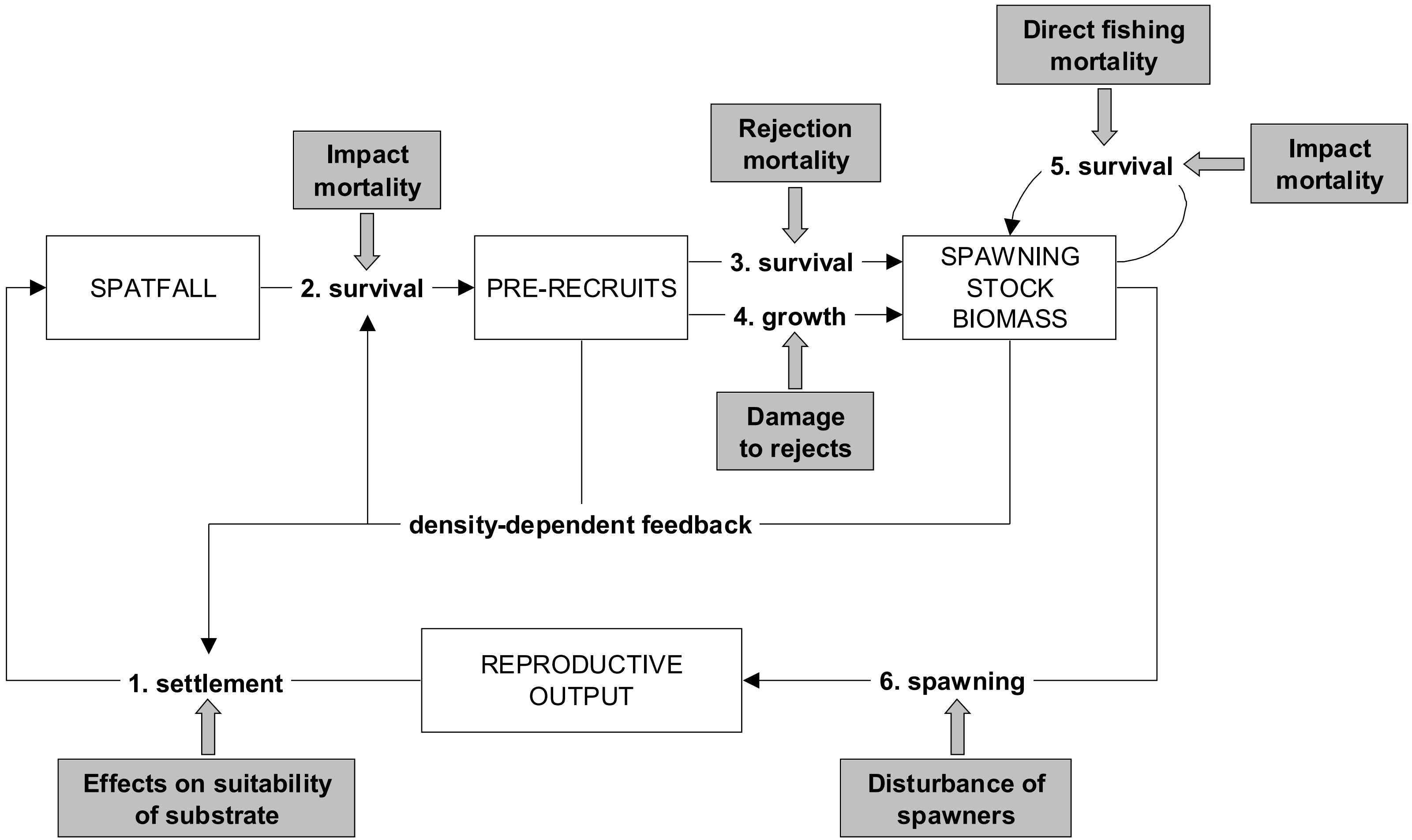


Figure 3.2 Cockle life-history processes (white boxes, black arrows) and the potential impacts of suction dredging (grey boxes and arrows). Numbers refer to the processes listed in Table 3.1.

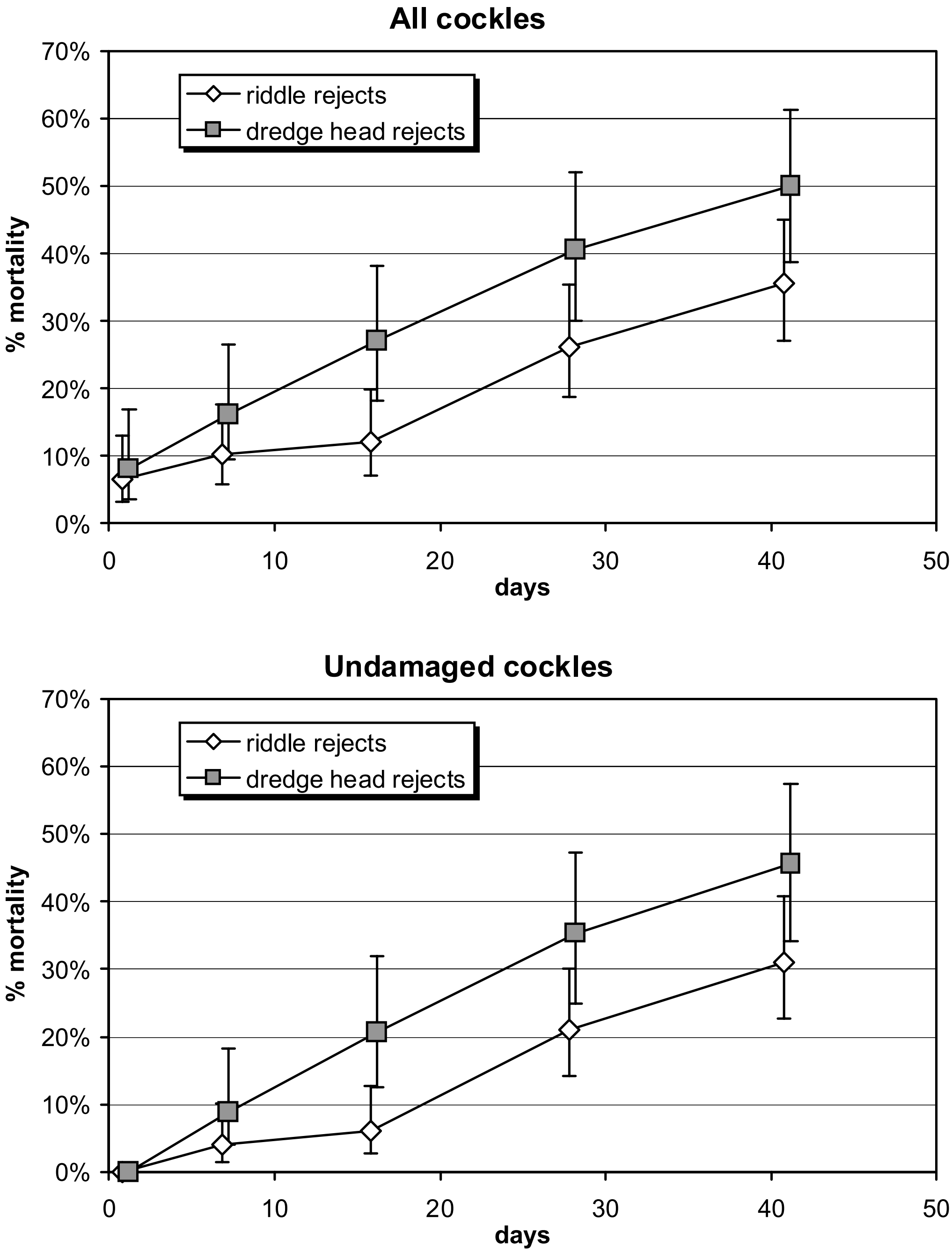


Figure 3.3 Mortality of cockles in a sample rejected at the dredge head and in a sample rejected at the riddle during experimental suction dredging in the Thames Estuary (original data from Wiggins, 1991). Data shown are observed percentage mortalities in an aquarium, with 95% confidence intervals according to a binomial distribution. Upper panel shows cumulative mortality of all cockles, including those showing immediate damage. Lower panel shows cumulative mortality excluding the initial damage.

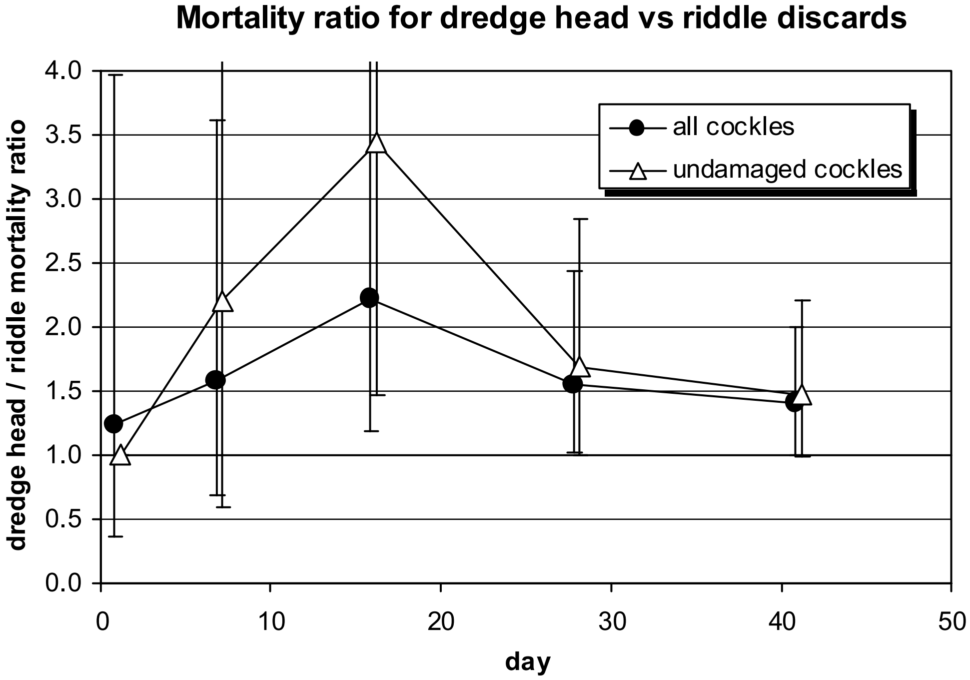


Figure 3.4 Ratio between mortality rates in a sample of cockles rejected at the dredge head and a sample of cockles rejected at the riddle during experimental suction dredging in the Thames Estuary (calculated from data in Wiggins, 1991). Approximate 95% confidence intervals for the ratios were estimated from 10,000 Monte Carlo simulations. Ratios are shown for all cockles and for cockles excluding those initially damaged. Upper 95% confidence limits for undamaged cockles on days 7 and 16 are 13.2 and 12.5 respectively.

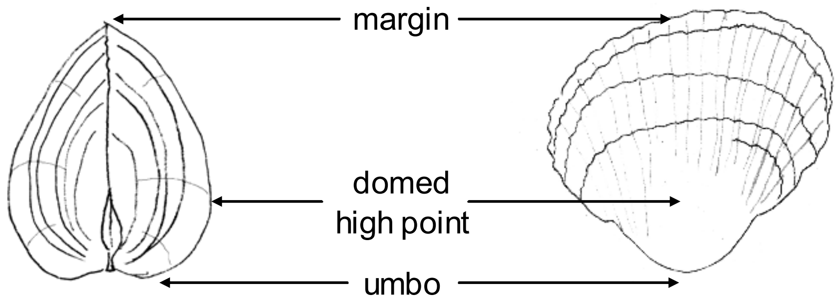


Figure 3.5. Diagram of a cockle shell, showing points of weakness identified by Coffen-Smout (1998).

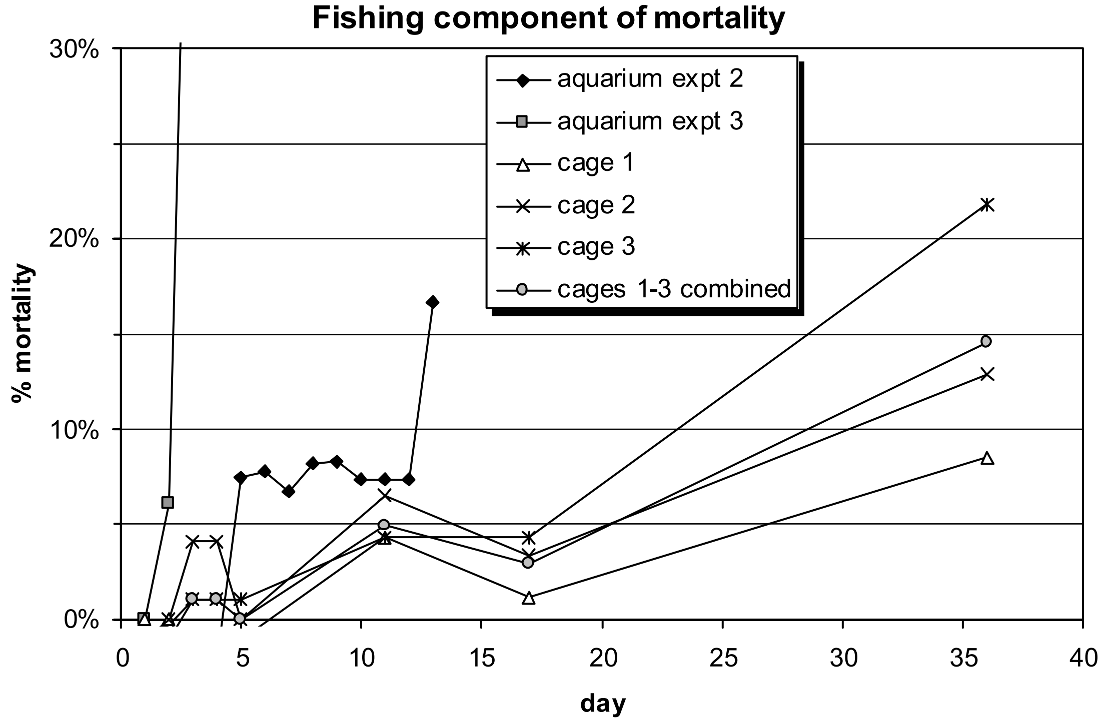


Figure 3.6 Fishing component of mortality of cockles rejected at the riddle during suction dredging in The Wash (data from aquarium and cage experiments by Mander & Trundle, 2001). Data shown are cumulative mortality rates of undamaged cockles collected from the discard side of the riddle, corrected for mortality observed in a control sample of hand picked cockles – **this represents the additional mortality inflicted by the fishing and rejection process only**. Experiments 2 and 3 were conducted in an aquarium, whilst cages 1-3 were placed on a natural cockle bed in The Wash. Aquarium experiment 3 showed 100% mortality by day 4, which is considered to be unrepresentative.

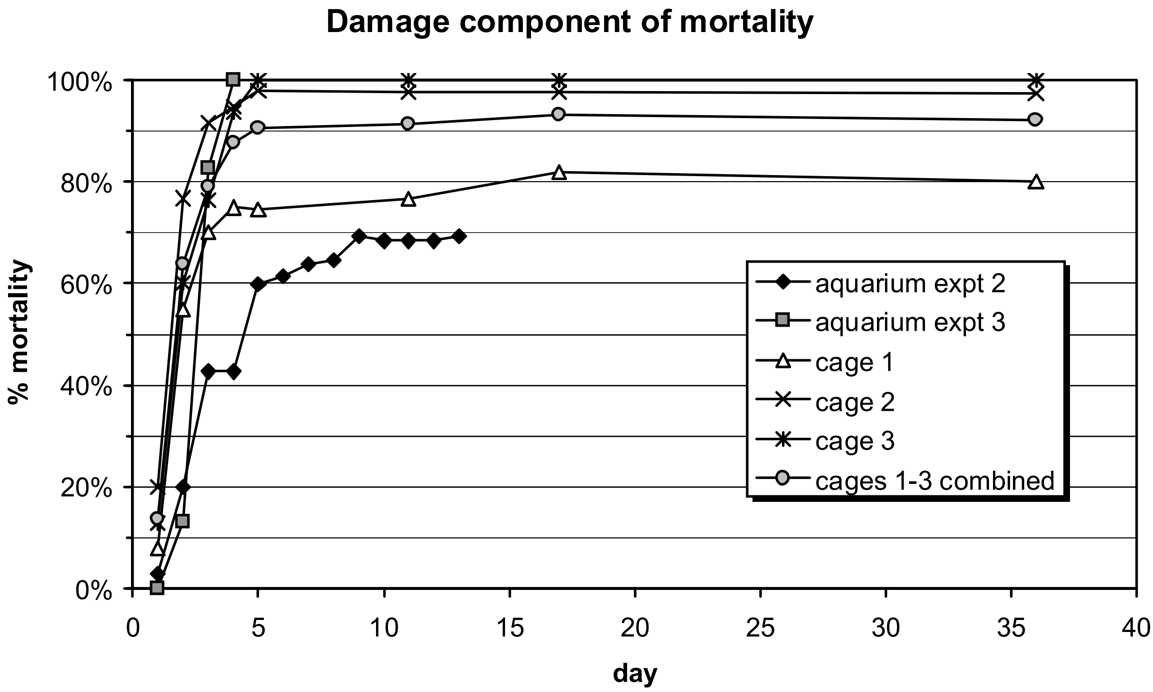


Figure 3.7 Damage component of mortality of cockles rejected at the riddle during suction dredging in The Wash (data from aquarium and cage experiments by Mander & Trundle, 2001). Data shown are cumulative mortality rates of damaged cockles collected from the discard side of the riddle, corrected for mortality observed in undamaged cockle discards and a control sample of hand picked cockles – **this represents the additional mortality inflicted by the damage only**. Experiments 2 and 3 were conducted in an aquarium, whilst cages 1-3 were placed on a natural cockle bed in The Wash.

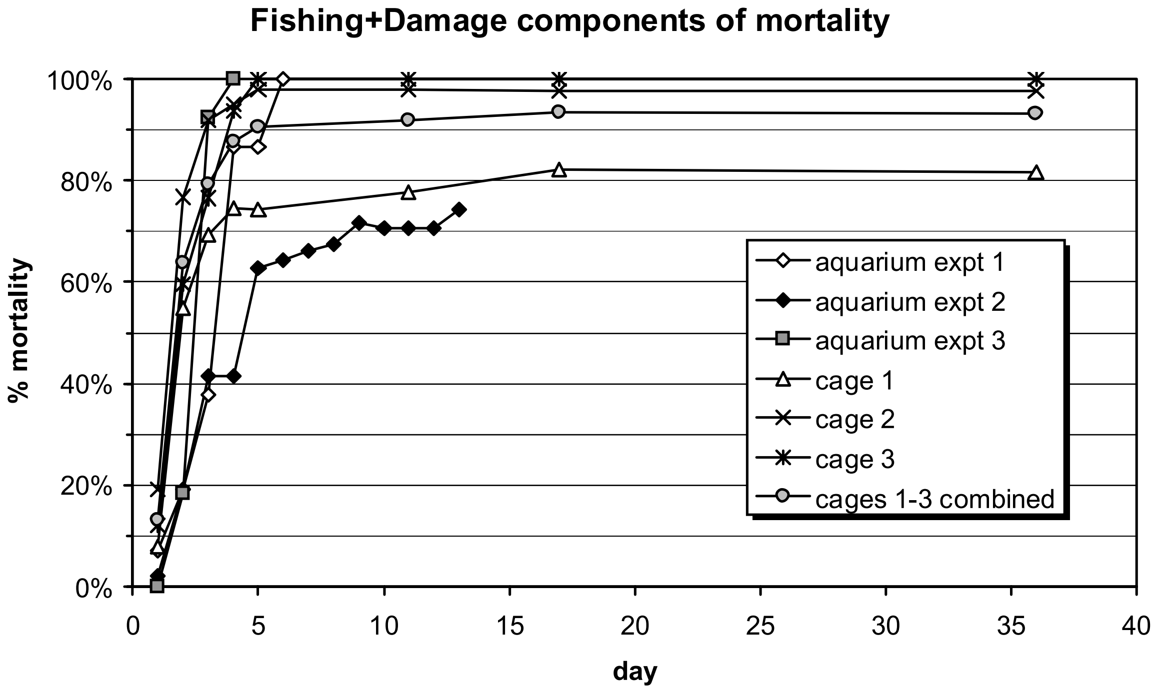


Figure 3.8 Combined fishing and damage components of mortality of cockles rejected at the riddle during suction dredging in The Wash (data from aquarium and cage experiments by Mander & Trundle, 2001). Data shown are cumulative mortality rates of damaged cockles collected from the discard side of the riddle, corrected for mortality in a control sample of hand picked cockles – **this represents the additional mortality inflicted by both the fishing process and damage.** Experiments 1-3 were conducted in an aquarium, whilst cages 1-3 were placed on a natural cockle bed in The Wash.

Table 3.1 The importance of potential dredge impacts at different stages of the life-history of cockles: blank cells, no impact; *, slight impact; **, moderate impact; ***, heavy impact; ?, unknown impact. See also Figures 3.1 and 3.2.

		Life-History Stage					
		1. Settlement	2. Spat survival	3. Survival to recruitment	4. Growth of pre-recruits	5. Survival of adults	6. Spawning
STAGE OF DREDGING PROCESS	1. Blade impact	?		*?		*	
	2. Dredge track	?	?	*?		?	
	3. Rejection at dredge head		?	***	**?		
	4. Travel up pipe			?	?		
	5. Passage through pump			?	?		
	6. Rejection at riddle		?	***	**?		
	7. Retention of catch					***	

Table 3.2 Recent cockle spatfall and survival of prominent year-classes for three beds in The Wash, summarised from ESFJC Annual Reports and Research Reports for 1998-2000. Fishing was limited to these three beds in 1998 owing to low stock levels elsewhere. Heavy, widespread spatfalls occurred on these three beds before and during the summer fishing season and inspection suggested that stocks were maintained in subsequent years.

Year	Season	Daseley's Sand	Breast Sand	Westmark Knock
1998	Summer	Fished June	Fished June	Fished June
	Autumn	Widespread spatfall	Widespread spatfall	Widespread spatfall
1999	Spring	No data	High densities of 1998 year-class	High survival of 1998 year-class
	Summer	Fished June-July	Fished June-July	Fished June-July
	Autumn	Sporadic spatfall	Low spatfall	Widespread spatfall, good survival of 1998 year-class
2000	Spring	Low densities of 1998 year-class	Dominant 1998 year-class	High mortality of 1999 year-class
	Summer	Not fished	Not fished	Fished July-August
	Autumn	Very heavy spatfall	Heavy and widespread spatfall, 1998 year-class at fishable densities	Heavy spatfall

Table 3.3 Estimated survival of cockle spat compared between areas, taken from Dare and others (2004). Data are for the 1991-98 year-classes, except for overwinter survival in The Wash which is for the 1986-90 year classes.

	1st winter survival (%)		1st year survival (%)	
Area	**Mean**	**Range**	**Mean**	**Range**
The Wash	9	0 – 22	9	<1 – 25
Thames Estuary	33	1 – 53	26	<1 – 46
Burry Inlet	51	40 – 67	41	27 – 64

Table 3.4 Calculation of indirect fishing mortality to cockles caused by suction dredging. It is assumed that there is 100% mortality of damaged cockles. Note that the rates refer to proportional values (ie probabilities) rather than instantaneous coefficients.

Calculation	Likely parameter values
Indirect fishing mortality	
=	
proportion of total stock that is dredged	Depends on catch limits and bed closures
×	
(dredge efficiency	~90%? variable between operators
×	
(rejection rate at the dredge head	Unknown, depends on size composition of dredged stock
×	
(damage rate of dredge head rejects	10% in good practice?
+	
(1 – damage rate of dredge head rejects)	
×	
mortality of undamaged dredge head rejects)	10-44% (based on 1-2.2 × 10-20% mortality of riddle rejects)
+	
(1 – rejection rate at the dredge head)	
×	
rejection rate at the riddle	Unknown, depends on size composition of dredged stock
×	
(damage rate of riddle rejects	10% in good practice?
+	
(1 – damage rate of riddle rejects)	
×	
mortality of undamaged riddle rejects))	10-20%
+	
(1 – dredge efficiency)	
×	
dredge track and blade impact mortality)	Unknown, but presumed low

4 Impacts on sediments and non-target biota

Suction dredging for cockles will have impacts that extend beyond the target species. This section considers the habitats and communities in which cockles occur in The Wash, and which therefore may potentially be affected by suction dredging, and examines the available information on the nature and scale of any such impacts. We also consider species with ecological dependencies on cockles (principally avian predators) which potentially could be affected by removal of cockles by the fishery.

4.1 The nature of cockle habitat

Cockles occur on intertidal sand and mudflats, where they are found on clean sand, muddy sand, mud or muddy gravel from the middle to lower intertidal (Tyler-Walters, 2003). Cockles themselves contribute to the accumulation of fine sediments by filtering fine particles from the water column to be deposited as faeces and pseudofaeces (Elliot and others 1998). Yates and others (1993a) found cockle density in The Wash to be most abundant in fine sandy sediments, often with little organic content, situated in the middle and upper shore levels. They also noted that cockles appeared to avoid clay, but could probably live equally well in fine and coarse sands. Although commercial densities of cockles occur predominantly in the more sandy areas of The Wash, in some years there may be significant stocks in areas of finer sediment on the Breast Sand and South Mare Tail. Detailed information on the particle size and organic content of intertidal sediments in The Wash is given by Yates and others (2002).

4.2 Benthic communities

Species co-occurring with cockles

Cockles occur as characteristic components of several communities in intertidal sands and muds. A full account of the biotopes in which cockles occur is beyond the scope of this report, but see Connor and others (1997), Elliott and others (1998) and the Marine Nature Conservation Review (MNCR) biotope dictionary at http://www.jncc.gov.uk/mermaid/. One of the most important biotopes for cockles is "polychaetes and *Cerastoderma edule* in fine sand or muddy sand shores" (MNCR biotope code LMS.Pcer). This is found at the lower levels of muddy sand shores, where the sediment is saturated with water for most of the time. Cockles are an important part of a community that consists of polychaetes (*Nephtys hombergii*, *Scolopos armiger*, *Pygospio elegans*, *Spio filicornis*, *Capitella capitata*), oligochaetes, the amphipod *Bathyporeia sarsi*, the snail *Hydrobia ulvae* and the bivalve *Macoma balthica*. This type of community often grades into other biotopes less important for cockles containing lugworm (*Arenicola marina*) and, in sheltered muddy sands, more oligochaetes, ragworms (*Hediste diversicolor*) and other species of polychaete. Cockles tend to be absent from adjacent biotopes higher on the shore dominated by *Bathyporeia pilosa* and *Corophium* spp. (amphipods). Another important biotope for cockles is "dense *Lanice conchilega* in tide-swept lower shore sand" (MNCR biotope code LGS.Lan). This occurs in medium to fine sand in tide-swept conditions where there are dense stands of the sand-mason worm *Lanice conchilega* (Budd, 2002). Cockles in this community co-occur with M*acoma balthica* and the polychaetes *Anaitides mucosa*, *Nephthys cirrosa*, *N. hombergii* and *Pygospio elegans*.

Benthic communities in The Wash

Yates and others. (2002) described ten biotope types in the intertidal areas of The Wash, based on surveys in 1998 and 1999. Cockles were present in nine types, but the most important were LMS.Pcer (described above) and LMS.MacAre ("Macoma balthica and Arenicola marina in muddy sandy shores") (Table 4.1). In the latter biotope, cockles were common alongside M. balthica, A, marina and Scolopos armiger, together with the polychaetes Pygospio elegans and Hediste marina and the burrowing amphipod Corophium volutator. This biotope type was common along the western and south-eastern shores of The Wash in 1998, but in 1999 much of the western shore had changed to a Wash variant of the type with lower silt content and low density or absence of cockles (LMS.MacAre1). LMS.PCer, where cockles occurred in commercially viable densities, occurred predominantly in the inner parts of The Wash in 1998, and had reduced in extent by 1999. Cockles were abundant in the biotope LMS.MacAre.Mare ("Macoma balthica, Arenicola marina and Mya arenaria in muddy sand shores"), characterised also by high abundance of Mya arenaria, but this type was uncommon in The Wash in both 1998 and 1999.

The biotopes described by Yates and others (2002) are not a comprehensive list of all those occurring in The Wash, but we consider that these are the only ones likely to receive impacts from suction dredging. They are largely covered under the Annex I habitat 1140 "Mudflats and sandflats not covered by seawater at low tide" and parts of 1160 "Large shallow inlets and bays", although these habitats also include environments outside the scope of the cockle fishery such as subtidal areas and eelgrass beds and other intertidal areas protected by the north Norfolk barrier islands and sand spits. Other significant Annex I habitats in The Wash include those in subtidal areas (1170 "Reefs" and 1110 "Sandbanks which are slightly covered by sea water all the time") and upshore of the cockle beds (1310 "*Salicornia* and other annuals colonising mud and sand", 1330 "Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)" and 1420 "Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)"). Cockles are known to occur occasionally in the shallow subtidal (eg Bailey and others 1999), but this is not thought to be significant in The Wash. An account of the subtidal habitats and communities in The Wash is given by Foster-Smith and others (1997). Subtidal communities in The Wash include dense beds of brittlestars (*Ophiothrix fragilis*) and species such as the sand-mason worm *Lanice conchilega* and the bivalve *Angulus tenuis*. Biogenic reefs of the tubeworm *Sabellaria spinulosa* are another important subtidal habitat type. All these subtidal habitats are, however, outside the areas likely to be fished by cockle suction dredgers. Diverse benthic communities exist in the deeper parts of the central Wash, but these are even further outside the area of operation for cockle suction dredgers.

4.3 Cockle predators in The Wash

Cockles are an important component of food webs in estuaries at all stages of their life histories. As described by Hancock & Urquhart (1965) and Hancock (1971), there are numerous potential predators of cockles, many of which are abundant in The Wash. The available information on cockle predators in The Wash is summarised by Dare and others (2004).

Crustaceans are the main predators of newly settled cockle spat, and the most important of these in The Wash are brown shrimp (*Crangon crangon*) and shore crab (*Carcinus maenas*). High settlement success of cockles in The Wash and elsewhere after some exceptionally cold winters has been attributed to delayed or reduced predation by these species (Beukema, 1991, 1992; Dare and others 2004). Brown shrimp take only the smallest cockles (2-3 mm, Pihl & Rosenberg, 1984). The abundance of this species (as measured by commercial landings per unit effort) has fluctuated three- to four-fold over the last two decades, but there is no suggestion that this has been linked to variations in the availability of cockle spat. These fluctuations appear to be related instead to environmental factors associated with primary productivity (nutrient levels and temperature) and possibly to the abundance of predators of shrimp (Lawler and others in prep.). Dare and others (2004) suggested that the converse may be true, with poor cockle spatfall success recorded in years of high shrimp abundance. Shore crabs are voracious predators of cockles, taking individuals mainly <15 mm shell length (Sanchez-Salazar and others 1987). Shore crabs will also feed on larger, damaged cockles, including discards from suction dredging (Mander & Trundle, 2000). There are no data on year to year variations in shore crab abundance in The Wash. However, given the broad range of other potential prey items in estuaries, we consider it unlikely that shore crab populations are ever truly limited by the availability of cockles in The Wash.

Common starfish (*Asterias rubens*) prey upon a wide range of bivalve species, including cockles of all sizes. They are occasionally recorded as feeding on cockles in The Wash, but they do not extend below the lowest levels of the intertidal and they are more important predators of mussels. Dare and others (2004) describe fluctuations in starfish abundance in The Wash during the last century that appear unrelated to the availability of cockles.

Flatfish are potentially important predators of cockles in The Wash. Flounder (*Platichthys flesus*) and plaice (*Pleuronectes platessa*), for example, are both known to prey upon cockle spat (Hancock & Urquhart, 1965; Berghahn, 1987). Very little is known about potential interactions between flatfish and their food supply (Dare and others 2004), but given the range of other possible prey items we consider it unlikely that cockle availability is a significant factor in flatfish population dynamics in The Wash.

The most important predators of cockles after settlement are undoubtedly birds. Gulls and some other species will feed opportunistically on fishery discards (Hancock, 1971; Mander & Trundle, 2000), and particularly the smaller size-classes of cockles feature in the diets of various species of shorebird (eg Prater, 1981). However, by far the most important species are the specialist bivalve feeders oystercatcher (*Haematopus ostralegus*) and knot (*Calidris canutus*). Both species are present in The Wash during the winter in Internationally Important numbers (1% or more of the east Atlantic flyway population) (Pollitt and others 2003). In winter The Wash regularly supports around 15,000 oystercatchers (almost 2% of the flyway population and more than 4% of the British population) and 70,000 knot (20% of the flyway population and almost 25% of the British population), and similar numbers are present on passage in late summer and early autumn (Pollitt and others 2003).

Knot are very important predators of cockle spat in The Wash, taking individuals in the size range 5-15 mm shell length (Goss-Custard and others 1977). Depletion of cockle spat by knot predation in The Wash is known to be very heavy at times. For example, a large bed of spat at Heacham disappeared during the autumn of 1990, having been heavily preyed upon by a flock of around 4,000 knot (Dare and others 2004). Dare (1999) estimated that the potential consumption of the knot population has exceeded the total numbers of cockle spat in The Wash over recent years. This potential is unlikely ever to be realised, partly because there is a minimum threshold prey density for profitable foraging by knot (Zwarts and others 1992), but also because alternative prey items are likely to be important in most years (Dare, 1999).

The bivalve *Macoma balthica*, which co-occurs with cockles but tends to be concentrated higher up the shore, is considered to be a more stable and dependable food resource for knot (Beukema and others 1993). Vulnerability of cockle spat to knot predation depends on the time taken to grow beyond the maximum size for knot predation, estimated by Zwarts & Blomert (1992) to be 12.5 mm shell length. Based on limited survey data for Heacham, Dare and others (2004) estimated that the 1986-90 year-classes reached average sizes of 12.5 mm at times varying from January to April, but noted that variation between individual cockles and between beds will be greater than this.

Knot predation on cockles precedes that by oystercatchers. Oystercatchers will take cockles of 15 mm and larger, but most typically in the size range 20-30 mm shell length (references in Goss-Custard, 1996). This size-range overlaps with that taken by the commercial fishery, but it is generally considered that cockles in their second winter form the bulk of oystercatcher prey (eg Horwood & Goss-Custard, 1977). Oystercatcher predation thus precedes the commercial fishery (*c.f.* Bell and others 2001), at least in terms of direct fishing mortality (see below). Oystercatchers will take various other invertebrates such as rag worms, but mussels are the only significant alternative prey in The Wash. Oystercatchers are thus heavily reliant on cockles and mussels in The Wash.

4.4 Evidence for effects of suction dredging on the sediment

Particle sizes

One of the principal concerns about the environmental effects of suction dredging for cockles is that it causes loss of fine particles with consequent destabilisation of the sediment. The conclusions of Piersma and others (2001) have already been summarised above in relation to the effects of dredging on cockle settlement (see Section 3.2 and also Piersma & Koolhaas, 1997). Intensive dredging close to the island of Griend in the Dutch Wadden Sea removed all stocks of cockles during 1988-90. Environmental impacts included the loss of fine silts from the upper sediments and an increase in median grain size. An increase of the tidal prism following cockle dredging caused stronger currents, and this effect was also exacerbated by decreased shelter from storms caused by loss of mussel banks after mussel fishing. Sediment stability was also compromised directly by removal of cockles and other bivalves, since bivalve pseudofaeces can play an important role in binding the sediment. The benthos was changed from a high biomass community dominated by bivalves to a less diverse and productive community dominated by short-lived opportunist species such as capitellid worms, characteristic of stressed and unstable environments.

Sediment characteristics at the Griend site did not return to the pre-dredged site until eight years later. Piersma and others (2001) postulated a negative feedback process cased by the removal of large filter-feeding bivalves. According to this hypothesis, the removal of the large bivalves causes sedimentary changes that lead to the decline of other filter feeders such as *Macoma balthica*. These filter-feeders play an important role in the build up of fine silts in the sediment, so their disappearance exacerbates the increase in sediment particle size, further discouraging the settlement of bivalve larvae. This is what Piersma & Koolhaas (1997) termed the ‘negative biodeposition spiral’ (see also Ens and others 2004b). Piersma and others (2001) suggested that the initiation of this process by cockle dredging could account for long-term changes in some other parts of the Wadden Sea from bivalve-rich muddy sediments to sandy sediments with a very low silt content and supporting very few bivalves. Ens and others (2004b) noted that this hypothesis probably does hold for the sandy parts of the central and western parts of the Wadden Sea, but not in the silty areas along the mainland coast and in the shelter of the Wadden Sea islands. These authors attributed lower cockle recruitment in areas closed to the fishery to the negative effects of adult abundance on cockle settlement (see Dare and others 2004).

The general conclusion from the Wadden Sea studies is that suction dredging potentially can have long-lasting effects on intertidal habitats, but this is very dependent on location and exposure to winds and tides. This conclusion is borne out from the results of studies elsewhere. Cook (1991) observed that after experimental suction dredging on Traeth Lafan in 1989, different parts of the beds responded differently to the dredging activity. Well defined dredge tracks, 1-2 cm deep were produced in all areas, but in the eastern part of the dredged area these tracks persisted for several weeks. The sediment in this area was harder and more cohesive than elsewhere, and the clearly defined dredge tracks appeared to act as a focus for large-scale erosion. Sediment was removed down to the anoxic layer along run-off channels, and a series of hummocks and hollows were apparent across the ground by two months after dredging. The area returned to a normal appearance by four months after dredging, following periods of severe winter weather. Elsewhere in the dredged area the sediment appeared to be more mobile, and the dredge tracks were re-filled without acting as a focus for erosion. No difference in particle size was noted between the areas, but Cook (1991) suggested that there may have been a difference in sediment cohesion due to biological (microbial) activity. Interestingly, a second period of dredging in 1990, albeit at a less intense level, caused no repeat of the erosion in the previously affected area. This suggests that the conditions leading to sediment modification by dredging can be temporally as well as spatially specific.

Although differences between sites and occasions suggest that it is difficult to draw meaningful generalisations about dredge impacts, there does appear to be a relationship between the degree of shelter and the vulnerability of sediments to dredging. Moore (1991) measured sediment parameters in dredged and undredged areas of Traeth Lafan (alongside Cook, 1991) and Blackshaw Flats (Solway Firth). Sediments at both sites were well sorted and with low proportions of fine particles, indicating sedimentary environments without much shelter and prone to regular disturbance by water movements. Under these circumstances Moore (1991) was not surprised to find little or no impact of dredging on sediment particle size or organic content. A later study at Traeth Lafan by Allen (1995) generally confirmed that particle sizes in the sediment did not show consistent differences between commercially dredged areas and undredged areas. These results contrast with those of Perkins (1988), who noted 15-22% reduction in the silt content following suction dredging for cockles in Auchencairn Bay, which is a very sheltered area of the Solway Firth. The fine particle (<63 μm) content of the sediment in Auchencairn Bay varied from 60-90% in the most sheltered areas down to 25-60% in the more open areas. This contrasts with mud contents of 4-13% in Traeth Lafan and 7-10% on the Blackshaw Flats (Moore, 1991).

Muddy sediments bound together by swards of *Zostera* spp. appear to be more likely than any other habitat to be disrupted by mechanical harvesting methods (Rees, 1996). Perkins (1988) noted a loss of eelgrass from fished areas following suction dredging in Auchencairn Bay during the spring and early summer of 1988, alongside the loss of fine silts and decreases in productivity and sediment stability in affected areas. Eelgrass beds do not occur in the fished areas of The Wash proper, but are present within The Wash and North Norfolk Coast cSAC in small areas of sediment sheltered by the north Norfolk barrier islands. It is unlikely however, that these areas would ever be targeted by cockle dredgers, even in the absence of preventative measures.

There are no specific data on changes in the sedimentary environment of The Wash as a result of suction dredging. Here, as in the Thames Estuary, the continued settlement of cockle spat in dredged areas (see Section 3.2 and Dare and others 2004), and the absence of any obvious, dramatic changes in the sediments suggest that suction dredging has not caused adverse changes in the structure and composition of intertidal sediments. This is possibly because the intertidal sediments within which the major concentrations of cockles occur are naturally very dynamic over much of The Wash, although commercial cockle beds also occur sporadically in some more sheltered, muddier areas. Sediment analyses by Yates and others (2002) suggest that the sediments in the main Wash cockle beds are more similar to those in Traeth Lafan and Blackshaw Flats than those in Auchencairn Bay: most of the sediment samples in the commercially fished areas were classified as 'sand', ie <30% of particles <63 µm (*c.f.* Figure 3.3.1 of Yates and others 2002 and Figure 5.10 of Dare and others 2004). Comparison of sediment data between 1986, before suction dredging started in The Wash, and 1998-99 shows that there has been no tendency for Wash sediments to become coarser over the period of suction dredging (Yates and others 1993a, 2002). This is a very broad scale comparison, but it does indicate that the sandiness of Wash sediments within the fished area are a natural circumstance rather than an effect of suction dredging. Further evidence from sediment sampling alongside controlled suction dredging in The Wash would be needed to confirm that suction dredging has no impact on sediment characteristics. For now we conclude that suction dredging has the potential in some places and at some times to cause loss of fine silts from intertidal sediments, with concomitant decreases in sediment stability and biological productivity, but that this probably has not occurred to any significant extent in The Wash.

Geochemical gradients

In the shallow eutrophic waters of the Limfjord, Denmark, Riemann & Hoffmann (1991) found that mixing of reduced particles from within the sediment after mussel dredging caused a decrease of oxygen and an increase in the average ammonia content in the overlying water column. It would be expected that dredging would cause similar chemical changes in the sediment. As we have already noted (see Section 3.2), disruption of subtle geochemical gradients in the surface layers of the sediment has the potential adversely to affect the settlement of invertebrate larvae (Woodin and others 1998). We concluded that this probably has not been a significant factor for cockles settling in The Wash. Johnson (2002) suggested that mixing of subsurface sediments and pore water caused by fishing is unlikely to be important in shallow water environments, because any effect is likely to be overridden by mixing from tidal currents, storm surges and wave action. Nevertheless, it is possible that at some times and locations disturbance of geochemical profiles by suction dredging could be a significant factor for cockles and other infauna.

As noted by Rees (1996), in all but the most free-draining sediments in estuaries a redox discontinuity exists only a few centimetres down into the sediment. In muddy sediments, the larger cockles may be dug into small pits in the anoxic sediment. Citing Richardson and others (1993), Rees (1996) suggested that cockle spat may respond to both physical and chemical disturbance by emerging at night, allowing them to be rolled by the tide into other (possibly more favourable) locations. Cook (1991) noted exposure of the anoxic layer during the sediment erosion noted in one area of Traeth Lafan after suction dredging (see above).

Whilst this was probably only an ancillary part of the overall impact on the cockles in the affected area, it does nonetheless indicate the level of disturbance to geochemical gradients that can be caused by dredging. According to Franklin & Pickett (1978), dredge tracks in the Thames Estuary remained visible for several months, disappearing after winter storms. Dredge tracks can remain covered by water at low tide, and Huggett (1992) suggested that this might affect oxygenation of the sediment, with implications for the infauna.

As with effects on particle size (see above), it is hard to make generalisations about the effects of dredging on sediment geochemistry. Much is likely to depend on shelter and biological (particularly microbial?) activity. It is recommended that this aspect of the sedimentary environment be studied as part of any future investigation into the effects of suction dredging in The Wash.

Recovery times

It is not possible to make definitive statements about the times taken for recovery of the sediment from the impacts of suction dredging at any given site. Piersma and others (2001) found that in a suction dredged area of the Wadden Sea near the island of Griend, eight years passed before the sediments returned to their pre-dredged state, a result of negative feedbacks between sedimentary and biological processes. Dare (1999) pointed out, however, that in this case the flats were systematically cleared by large vessels working in parallel tracks, a far more efficient and intensive scale of operation than anything practised in the UK. Cook (1991) noted that the parts of Traeth Lafan which suffered erosion after suction dredging had at least superficially returned to normal within four months, following winter conditions of strong winds and heavy wave action. Woodin and others (1998) noted that geochemical gradients disrupted by sediment disturbance could return to normal within minutes to hours. The lack of any evidence for sediment changes in The Wash following suction dredging suggests that the recovery times here are closer to this short time-scale than the long time-scale recorded in The Wadden Sea. However, it is important that this hypothesis should be tested rigorously in an experimental context.

Any future study of dredging effects on Wash sediments will need to take into account the specific nature of the sedimentary environment. It is beyond the scope of this report to give a detailed account of the sedimentary processes in The Wash, but we note that previous studies have demonstrated that the major source of Wash sediment is marine rather than from fluvial inputs. Dugdale and others (1987) concluded that the supply of sediment to The Wash is generated and sustained by erosion of the sea bed off the Lincolnshire coast. Evans & Collins (1987) suggested that the boundaries of mud and sand flats and saltmarshes in The Wash generally do not migrate because of a balance between the rate of *in situ* accretion of sediments from marine sources and the rates of sea level rise and subsidence. Any alteration in the balance of these processes, caused for example by climate change, conceivably could influence the response of the sediment to suction dredging.

4.5 Evidence for effects of suction dredging on benthic invertebrate communities

Short-term and medium-term effects

There is a large literature on the impacts of mobile fishing gear on benthic communities (eg Jennings & Kaiser, 1998; Collie and others, 2000; Johnson, 2002). Johnson (2002) highlighted some of the life-history, ecological and physical characteristics of marine organisms that affect their vulnerability to fishing impacts. In general, mobile, fast-growing species with high fecundity and fast generation times will suffer less impact than sessile, long-lived species. Benthic communities in naturally dynamic environments may be relatively robust to fishing disturbance (eg Currie & Parry, 1996, 1999), whereas more stable environments such as rock or gravel, where communities are likely to include more long-lived or fragile species, tend to be more heavily impacted (eg Bradshaw and others, 2000).

A number of studies have focused on the effects of hydraulic dredging for various bivalve species in intertidal and shallow subtidal environments (eg Kauwling & Bakus, 1979; Kaiser and others 1996; Tuck and others 2000; Hauton and others 2003; and see reviews by Fowler, 1989 and Huggett, 1992). Owing to the gear-specific and habitat-specific nature of dredging impacts, we will restrict our attention to those studies that have specifically addressed suction dredging for cockles.

The earliest studies of effects of cockle dredging on non-target organisms were in the Dutch Wadden Sea and Oosterschelde in 1979 and 1980 (de Vlas, 1982, summarised by de Vlas, 1987 and cited by Ens and others 2004b). As highlighted by Ens and others (2004b), repeated crossing of the ground with dredges will cause increased bycatch of benthic fauna because the depth of penetration is increased beyond the 4-5 cm achieved on the first pass. Around 45% of the fished area considered by de Vlas (1982) was touched at least twice by the dredges. Data summarised by de Vlas (1987) show that whilst much of the macrobenthos in the dredge tracks was washed out of the sediment by dredging, at least some of the washed out animals could survive. Rates of washing out and mortality depended very much on species and their burrowing depths. Adults of the large bivalve *Mya arenaria* exists beyond the penetrating depth of the dredges, even after repeated passes, and none were recorded as washed out. By contrast, up to 60% of juvenile *M. arenaria* were washed out, and similar proportions were killed. Likewise, up to 70% of adult and up to 100% of *Macoma balthica* were washed out, and up to 30% were killed. The gastropod *Hydrobia ulvae*, which is small, robust and lives at the sediment surface, was completely washed out of the sediment, but at least 99% survived. Various polychaete species, differing in depth preference, body size and fragility, showed wash out rates ranging from 0-5% (*Heteromastus filiformis* and *Lanice conchilega*) up to 90-100% (*Pygiospio elegans* and juvenile *Arenicola marina*) and mortality rates ranging from 0-5% (*L. conchilega* and adult/sub-adult *A. marina*) up to 50% (*Heteromastus filiformis*). The most important benthic impact was the removal of adult cockles. Biomass of non-target benthos was also reduced immediately after dredging, but three weeks later had returned to levels comparable with undredged areas, albeit with some changes in species composition. Despite this fast recovery, de Vlas (1987) calculated that there was a net loss of secondary production in dredged areas, amounting to 53 g AFDW (ash free dry weight) per m^2 in the Wadden Sea and 11 and 397 g AFDW per m^2 in two areas of the Oosterschelde. Interpreting Figure 6 of de Vlas (1987), this appears to represent a loss of about 10% of annual secondary production in the Wadden Sea. De Vlas (1987) commented that the removal of secondary production by cockle fishing was probably less than that added by eutrophication.

These early studies in the Wadden Sea were undertaken after dredging with a mixture of batch dredges and continuous delivery suction dredges. The former type used water jets to fluidise the sediment, but needed lifting from the bottom to recover the catch. The results of the studies are therefore no more than indicative of the types of impact that could be expected after dredging with modern suction dredges. More recent work in the Wadden Sea was undertaken as part of the EVA II project by Ens and others (2004a) (summarised by Ens and others 2004b). Comparing these recent results with those of de Vlas (1982), Ens and others (2004b) comment that there is no indication that new fishing gear and techniques have reduced mortality of non-target benthic fauna. Higher levels of mortality after fishing were observed in *Macoma balthica* (45-50% in spat and adults combined, compared with 5-30% in spat and 0-25% in adults in the earlier study). Higher mortality was also observed in the polychaetes *Hediste diversicolor* (30-55% compared with 0-20%), *Scolopos armiger* (60-100% compared with 5-30%) and *Lanice conchilega* (55-70% compared with 0-5%). Only one, *Heteromastus filiformis*, showed lower mortality in the later study (up to 25% compared with up to 50%). Despite the high mortality of these species after dredging, Leopold and others (2003a) (cited by Ens and others 2004b) was unable to demonstrate consistent negative relationships between invertebrate densities and fishing effort. Declines due to fishing effort could be identified in mussel clumps and *Arenicola marina*, but the relationship depended on year of fishing in *Macoma balthica*, *Lanice conchilega* tubes and small worms. A positive relationship with fishing effort was found for live *Lanice conchilega*. The study showed no evidence that dredging disturbance had caused an increase in the numbers of worms at the expense of bivalves, as had been predicted from previous studies (Reise, 1982). However, a study in a more restricted part of the western Wadden Sea did show some evidence of this pattern (Kraan and others 2004, cited by Ens and others 2004b).

The first relevant study of suction dredging impacts in the UK was by Perkins (1988) in Auchencairn Bay, a sheltered area of the Solway Firth. The results of this study with respect to sediment changes are summarised in Section 4.4, above. The major loss of eelgrass beds after dredging was also described. As highlighted by Fowler (1989), eelgrass beds are also notable for their associated benthic communities. Aside from the loss of eelgrass, the major impact recorded by Perkins (1988) was a significant decrease in the density of *Macoma balthica* in the dredged areas. Some of the disturbed *Macoma* may have been moved to other areas by tidal currents rather than killed directly by dredging, but Fowler (1989) reported a ‘wreck’ of *Macoma* on the strand line after suction dredging in another part of the Solway Firth. Of the other species recorded by Perkins (1988), no clear dredging impacts were noted in *Hydrobia ulvae*, *Angulus tenuis*, *Nephtys* sp. or *Arenicola marina*. In the case of the last two species, this was probably because they occur below the surface levels of the sediment affected by dredges (but note that Leopold and others (2003a) did find an effect of dredging on *Arenicola* in the Wadden Sea).

The effects of suction dredging for cockles on the benthic communities of Auchencairn Bay were also studied by Hall & Harding (1997), who also made comparisons with the effects of tractor dredging (see also Section 5.3). Compared with an unfished control area, the abundance and number of species of benthic invertebrates were signficantly reduced after dredging. Of the dominant non-target species, only *Owenia fusiformis* and *Pygospio elegans* showed significant reductions after dredging. Multivariate analysis showed that overall benthic community composition differed between control and dredged sites immediately after dredging, but no difference was apparent after a week. Taken as a whole, the results indicated recovery of benthic community structure by eight weeks. Overall, despite expressing caution about the ability of the statistical methods to detect meaningful changes, Hall & Harding (1997) concluded that after initial high mortality of non-target benthic fauna, recovery of sites disturbed by suction (and tractor) dredging is rapid and that there are probably low overall effects on populations.

Moore (1991) came to similar conclusions with respect to suction dredging for cockles in another part of the Solway Firth (Blackshaw Flats) and at Traeth Lafan. At Traeth Lafan the immediate effects of dredging were to decrease the number of species and the overall abundance of benthic invertebrates, whilst only *Hydrobia ulvae* showed a significant decrease at Blackshaw Flats. Comparison between control and impacted sites showed that complete recovery had occurred by three months after dredging, with few effects apparent after a week. These results refer to recovery after a single experimental period of intensive dredging at each site. Moore (1991) also examined the effects of commercial dredging over three months at Traeth Lafan. Comparison between dredged and control areas was complicated by significant differences in the communities before dredging, but it appeared that few changes could be attributed to dredging. The polychaete *Pygospio elegans*, which lives in semi-permanent tubes which may be uprooted by dredging, declined by 87% in the dredged areas, whereas no change occurred in the control areas. Densities of *P. elegans* remained at a lower level two months after dredging had ceased. Otherwise the most important change was a significant reduction in the density of *Macoma balthica* in the dredged areas. In a parallel study of suction dredging in Traeth Lafan, Cook (1991) recorded significant reductions in *Macoma* in dredge tracks compared with adjacent areas, with damage rates as high as 21%. Damage rates of 26% were recorded in *Macoma* rejected at the riddle.

Impacts of suction dredging on *Macoma* were also found by Hiddink (2003) in a recent study in the Dutch Wadden Sea. Densities of *Macoma* spat were lower in dredged than in undredged areas, and densities of the same year-class remained lower in the dredged areas one year after dredging. No effects of dredging on densities of *Hydrobia ulvae* were found, but the dredged area appeared to become less suitable for mussel settlement, probably owing to reductions in the availability of dead and living cockle shells and *Lanice* tubes. Hiddink (2003) suggested that the effects on *Macoma* extended beyond the immediate dredge-related mortality and redistribution caused by dredging, indicating that the habitat becomes unsuitable for *Macoma* after dredging. This accords with the findings of Piersma and others (2001) (see also Sections 3.3 and 4.4 for their conclusions about the effects of dredging on cockle settlement and sediment composition). These authors described a loss of *Macoma* (along with cockles and mussels) from an area of the Wadden Sea after dredging in 1988. Low rates of settlement of *Macoma* and other bivalve species was observed until 1996, eight years after dredging. This was attributed to a negative feedback between biological and sedimentary processes (see Section 4.4) affecting the suitability of the substrate for settlement.

Conclusions about impacts of suction dredging on benthic communities are rather similar to those about effects on sediments (Section 4.4). Again, the scale and duration of impacts appear to be very individual to sites and occasions, but as a general rule greater impacts are observed on communities in fine sediments in sheltered locations than on coarser sediments in more exposed areas. There is no doubt that there can be high levels of immediate mortality to invertebrates within dredge tracks and within the sediment layers penetrated by the dredges. This has been shown in the Wadden Sea, Solway Estuary and Traeth Lafan. In dynamic environments such as Traeth Lafan and Blackshaw Flats, and perhaps even in some more sheltered areas such as Auchencairn Bay, the effects on benthic invertebrates appear to be short-lived. In the Wadden Sea there is more concern about effects extending beyond immediate mortality, with evidence of long-term sediment changes that affect the recruitment of bivalves and probably other invertebrates. Several studies have suggested that the bivalve *Macoma balthica* may suffer high mortality after dredging, due partly to direct damage from dredges and partly to being dislodged from the sediment and transported elsewhere. This may be a particular concern in relation to resources for shellfish-eating birds in The Wash (see Section 4.6), although Dare (1999) pointed out that *Macoma* tend to be most abundant upshore of the commercial cockle beds. The possibility that this upshore distribution is an effect of dredging can be excluded, since this distribution pattern was apparent before dredging started in The Wash. Data from Yates and others (1993a, 2002) show that sediments within the main cockle beds in The Wash tend to have a low silt content, and that this was true before suction dredging started in The Wash as well as in more recent years. In Section 4.4 we suggested that this demonstrated a dynamic sedimentary environment, relatively robust to suction dredging, although it is worth noting that cockles also occur in some more sheltered locations where suction dredging might be expected to have greater impacts. We might similarly conclude that benthic invertebrate communities in The Wash are likely to be highly dynamic and therefore quick to recover from any impacts of suction dredging. Comparison of invertebrate density data between 1986 (before suction dredging), 1998 and 1999 does indeed show that there can be major changes in invertebrate community composition, even over the course of a single year (Yates and others 2002, and summarised in Table 4.2). Increases as well as decreases in density of individual taxa occurred between 1998 and 1999. However, changes between 1986 and the more recent years suggest more cause for concern. The distribution of a number of species became more restricted between 1986 and 1998, whereas the distribution and density of phyllodocid worms were increased (Yates and others 2002). In the case of highly mobile and/or short-lived species, such as the amphipods, the populations would be expected to be very dynamic, but the sustained decrease in the relatively long-lived bivalves *Macoma balthica* and *Mya arenaria* may be more significant with regards to possible effects of dredging. On the face of it, this runs against our earlier conclusion that the suitability of sediment for bivalve settlement is unlikely to be affected by suction dredging for cockles in The Wash (Section 4.4). It should be emphasised, however, that these comparisons take no account of the distribution of species in relation to cockle fishing areas, and involve a small number of years for naturally dynamic communities. For now, we cautiously conclude that, with the possible exception of *Macoma*, benthic invertebrate communities over much of The Wash probably are resilient to suction dredging for cockles by virtue of their naturally dynamic nature. More detailed analysis of historical data, and focused benthic sampling programmes alongside experimental dredging in The Wash will be needed to confirm this conclusion. It is also worth noting that there may be some areas of The Wash where benthic communities are more vulnerable to suction dreding than in the main commercial areas. These include the more sheltered, muddier areas (see Section 4.1), and possibly also sandy areas supporting communities with important 'structural' components (principally *Lanice* tubes). Cockles co-occur with *Lanice conchilega*, as part of an important intertidal biotope within The Wash (Section 4.2), although this is unlikely to form a significant part of the total commercial stock (see Table 4.1). Finally, given that suction dredging possibly affects potential surfaces for mussel settlement, eg by removing *Lanice* tubes and exposing or burying dead bivalve shells (Hiddink, 2003), further investigation is warranted into possible interactions between suction dredging and mussel settlement in The Wash.

Recovery times

Recovery times for benthic communities impacted by suction dredging are closely related to recovery times for their sedimentary environment, and the same general conclusions apply (Section 4.4). Dynamic communities in exposed situations recover very quickly. At Traeth Lafan and Blackshaw Flats, recovery after a single period of intense dredging was complete after three months, and there were few differences between dredged and control areas after only a week (Moore, 1991). Sustained commercial dredging at Traeth Lafan over three months also caused few significant changes in the benthic community compared with an unfished area. In the more sheltered Auchencairn Bay, severe and potentially long-term impacts have occurred in the muddy eelgrass beds (Perkins, 1988), but studies at the same site by Hall & Harding (1997) showed recovery of benthic community structure within two months after dredging. There is some evidence that *Macoma balthica* may be more severely impacted than some other species, particularly in the longer term. Hiddink (2003) noted lower densities of *Macoma* after dredging in the Wadden Sea that persisted for at least a year. Piersma and others (2002) found that recovery of recruitment by *Macoma* and other bivalve species took eight years after dredging in an area of the western Wadden Sea.

Given the sedimentary nature of the commercial cockle fishing areas over much of The Wash (exposed, dynamic, low in silt – see Section 4.4), it would be expected that recovery times would be relatively short – perhaps similar to Traeth Lafan. This requires confirmation in an experimental context, and particular attention needs to be paid to the response and recovery of *Macoma balthica*. In some years suction dredging occurs in muddier, more sheltered areas of The Wash, including parts of the Breast Sand (especially upshore of Scotsmans Sled) and the South Mare Tail. Benthic recovery times in these areas would be expected to be longer than in the more exposed, dynamic areas where dredging occurs in most years.

4.6 Ecosystem effects of suction dredging

Changes in the benthic environment and in the communities that it supports are clearly ecosystem effects of dredging. Infaunal communities on soft sediments contribute to physical structure and stability of their environment (eg Thrush and others 1996), and the role of bivalves in biodeposition has already been highlighted (Section 4.4). However, little else is known about how dredging might affect the ecological relationships between the species in these communities. In this section, therefore, we concentrate our attention on the higher trophic levels in estuaries. A variety of fish and macro-invertebrates prey upon cockles (Section 4.3) and other benthic species that may be disturbed by suction dredging, but there is no information available that would allow us to judge how suction dredging might affect these predators in The Wash. By contrast, much is known about interactions between estuarine birds and their invertebrate prey. We review the available evidence that suction dredging for cockles affects these birds, concentrating mainly on the species that feed on cockles but also considering bird species that depend on other benthic invertebrates that may be affected by dredging.

Shorebird-fishery interactions

As described in Section 4.3, The Wash supports Internationally Important numbers of knot and oystercatcher, the two most important avian predators of cockles. Dare (1999) provides a detailed description of the relationship of these two species with their food supply and shellfisheries in The Wash. His conclusions with respect to cockle and mussel fisheries in The Wash were: (i) cockle dredging is unlikely to adversely affect knot populations in The Wash, since the fishery does not take the spat upon which the knot feed; (ii) whilst knot predation on cockle spat is potentially very heavy in the autumn, it is unlikely to reduce fishery yields since this occurs 1-2 years before recruitment to commercial size; (iii) oystercatchers may compete directly with fishermen for harvestable cockles and mussels, since they are capable of taking significant proportions of the stocks, especially when stock abundance is low; and (iv) the modern Wash dredging fleets (for cockles and mussels) can out-compete the birds for their prey.

Conclusions (i) and (iii) were generally borne out by Atkinson and others (2003). Conflict between commercial and conservation interests have long been a major political issue in relation to shorebirds and shellfisheries (eg Davidson, 1967; Andrews, 1974), and concerns had been expressed about possible linkages between declines in knot and oystercatcher numbers in The Wash and the effects of fisheries on their food supply (Dare, 1999). Between the mid-1980s and the late 1990s numbers of oystercatcher wintering in The Wash declined from 30,000 or more to around 10,000, whilst over the same period knot declined from 80,000 or more to around 40,000 (Atkinson and others 2003). In an attempt to explain these declines in terms of population processes, Atkinson and others (2003) used ringing data to estimate survival rates for oystercatcher and knot wintering in The Wash between 1970 and 1998. Three periods of mass mortality were identified in oystercatchers, and it was found that much of this mortality could be attributed to cold weather and periods when cockles and mussels were both at low levels of stock abundance. When combined with estimates of recruitment to the Wash oystercatcher population, incorporation of the survival patterns into a population model provided a close fit to the observed decline in numbers. No such relationship was identified between knot survival and shellfish abundance, but Atkinson and others (2003) did suggest that recruitment of juveniles to the Wash population of both bird species was low during periods of low shellfish abundance.

Stillman and others (2003) used a model of the foraging decisions and competitive interactions of individual oystercatchers to predict their mortality in The Wash. Using data on oystercatcher population size, annual variations in cockle and mussel abundance and temperature, the model correctly identified the years in which the observed overwinter mortality was either low or high. Oystercatchers were both observed and predicted to die when much of the available food supply was still available. In the model, this was because interference competition excluded the least dominant birds from the food supply so that the least efficient foragers died before the food supply was exhausted. Prior to the current closure of the cockle fishery in the Dutch Wadden Sea, shellfish stocks corresponding to 60-70% of the average total food requirement of shellfish-eating birds were set aside for those birds (Common Wadden Sea Secretariat, 2002). The management objective was that bird populations should be maintained at the average levels of the 1980s. Reviewing the success or otherwise of the food reservation policy in the Wadden Sea and the Oosterschelde, Ens and others (2004b) concluded that the policy had failed to prevent food shortages for the reference numbers of shellfish-eating birds in both areas in years with fishery-induced food shortage (in the Wadden Sea, the food shortage for oystercatchers was probably the result of the absence of intertidal mussel beds during the 1990s rather than to a shortage of cockles). Based on the results of behaviour-based models applied to five different areas (including The Wash), Goss-Custard and others (2004) concluded that even leaving enough shellfish to meet 100% of the birds' total food requirement may fail to ensure that oystercatchers survive the winter in good condition. They suggested that between 2.5 and 7.7 times this amount must be available in autumn if most oystercatchers are to survive until spring, even if alternative prey species are available. It is important to note that wintering oystercatchers are very site faithful (Ens & Cayford, 1996), thus there is little capacity to compensate for food shortages in one area by an overabundance of food in another.

These studies draw a strong linkage between oystercatcher mortality and supplies of cockles and mussels. It is relevant to ask whether this necessarily implies a linkage between oystercatcher mortality and shellfisheries. Conclusion (iv) above, from Dare (1999), implies that there is such a linkage in The Wash. However, Bell and others (2001) suggested that at least in the Burry Inlet there may not be a linkage between cockle fishing and the availability of food to oystercatchers. Cockle mortality was relatively constant between years, such that fluctuations in stock abundance were controlled principally by variations in spatfall success. Based on a simple model of depletion of cockles by shorebirds and the fishery, Bell and others (2001) suggested that provided cockle mortality from bird predation and fishing does not exceed a combined threshold of 40-50% of cockles of age 2+, variations in mortality from these sources are balanced by variations in mortality from other, unaccounted sources. In other words, the combined effects of other (unknown) mortality sources are compensatory rather than additive to fishing and bird predation. Thus, provided fishing mortality and bird predation remain within the compensatory capacity, neither should add significantly to overall cockle mortality. Although, given overlaps in the size ranges of cockles taken by oystercatchers and the fishery, there may still be some scope for competition between birds and fishermen, the general conclusion is that cockle fishing in the Burry Inlet probably does not affect the quantities of cockles available to oystercatchers.

As noted in Section 3.2, the existence of any such compensatory mechanism for cockles in The Wash is purely speculative. As a background to management, it will certainly be important to determine the relative contributions of fishing and bird predation to patterns of cockle mortality in The Wash. This is unlikely to be possible with historical data, however, owing to the low precision of survey estimates of cockle abundance (Dare and others 2004). Even if a compensatory mechanism does exist, it is much more likely that suction dredging for cockles does affect the food supplies of oystercatchers in The Wash than that hand raking for cockles affects the food supplies of oystercatchers in the Burry Inlet. This is because suction dredging will cause additional mortality of pre-recruit cockles that are rejected by the dredges. In Section 3.3 we tentatively estimated that in dredged this might add a further 27% mortality to that inflicted directly by fishery removals (there is considerable uncertainty around this estimate). The affected pre-recruit cockles are likely to include size-classes important to oystercatchers, particularly as the summer fishery precedes the arrival of oystercatchers in the following winter. In practice, the impact of suction dredging on the supply of cockles to oystercatchers will depend on the relative spatial distributions of commercial and undersized cockles. If fishing is restricted to areas of mainly commercial cockles (see Section 5.3), then the scope for oystercatcher-fishery interactions may be fairly small, although there may be some overlap in the sizes of cockles taken. It should also be remembered that the effects of the cockle fishery should not be considered in isolation, since oystercatchers also depend heavily on mussels. As highlighted by Atkinson and others (2003) and Stillman and others (2003), the relaying of mussel seed in intertidal areas of The Wash may play an important role in sustaining oystercatcher populations.

Conclusions (i) and (ii) above, from Dare (1999), were that cockle fishing does not affect knot populations and that knot predation does not affect the supply of cockles to the fishery. With regards to the second conclusion, Dare and others (2004) presented evidence that heavy knot predation can at times have at least localised impacts on the numbers of cockles surviving to recruit to the fishery (see Section 4.3). We have already described the results of Atkinson and others (2003) that demonstrate that the availability of cockles probably has not influenced the survival of knot in The Wash over recent decades (although there remains the suggestion that knot recruitment may be lower in years of low cockle abundance). The finding of Dare and others (2004) that patterns of cockle spatfall in The Wash have not changed over recent years compared with the historical period, and our (related) conclusion that suction dredging probably does not affect cockle settlement in The Wash (Section 3.2) both support the idea that knot have not been affected by the cockle fishery. However, this conclusion appears not to generalise to all sites. Piersma & Koolhaas (1997) monitored biological and environmental changes after suction dredging in an area of the Wadden Sea important as an autumn staging point for knot (see also Piersma and others 2001). Numbers of knot fell dramatically during the first four years, and showed only modest recovery during the next four. This coincided with losses of silt from the sediment and consequent failures of recruitment of bivalves including cockles and *Macoma*, both important prey items for knot (see Sections 4.4 and 4.5). The conclusion of no impact on knot in The Wash does not take into account potential effects on alternative prey species (Section 4.5). According to Dare (1999), most of the *Macoma* in The Wash occur on the upper shore, above the area of commercial cockle dredging. However, Dare (1999) also highlighted a lack of information on the structure and dynamics of the *Macoma* population in The Wash. Given the likely importance of this alternative food supply, and the likelihood that at least within fished areas *Macoma* may be significantly impacted by suction dredging (see Section 4.5), this aspect of potential dredge impacts on knot warrants further investigation.

Our conclusions so far relate to only two species out of the many shorebirds that feed in the intertidal areas of The Wash. Given that dredging is likely to have at least short-term effects on non-target benthos (Section 4.5), there is the potential for fishing operations to affect food supplies for birds that do not depend directly on cockles. Leopold and others (2003b) (cited by Ens and others 2004b) reported significant changes in abundance of nine species of shorebird in the Wadden Sea following the disappearance of mussel beds. Most of the bird species were not directly dependent on mussels, feeding instead on benthic invertebrates associated with mussel beds. Both positive (ringed plover, dunlin, sanderling, bar-tailed godwit, redshank and greenshank) and negative (avocet, spotted redshank and turnstone) trends were observed, suggesting that change does not always mean decline in availability of prey species. Very little is known about how suction dredging for cockles affects the overall food supplies for birds other than oystercatcher and knot. Ferns and others (2000) observed that after experimental tractor dredging for cockles in The Burry Inlet, bird feeding increased at first on the harvested areas, with gulls and waders taking advantage of invertebrates made available by the harvesting. However, in the muddier areas which were slow to recover after dredging (*cf* studies cited in Section 4.5 and see Section 5.3), activity by curlews (*Numenius arquata*) and gulls remained significantly reduced for more than 80 days after harvesting. Oystercatcher activity was reduced for more than 50 days. Similar short-term increases in bird feeding activity were reported by Mander & Trundle (2000) after cockle relaying experiments in The Wash. Suction dredging activity is likely to cause at least some loss of secondary productivity in the benthos, as shown by de Vlas (1987), but it is not known how significant this might be for benthivorous birds in The Wash. Given the dynamic nature of Wash sediments and benthic communities (Sections 4.4 and 4.5), it might be assumed that the impacts would be small, but detailed analysis of invertebrate community data in relation to bird feeding requirements would be needed to confirm this. Yates and others (1993a) describe models relating bird densities to invertebrate densities and sediment characteristics, but no clear pattern emerges with respect to the benthic species that might be affected by dredging.

We conclude that suction dredging for cockles in The Wash probably has not impacted on knot populations, may contribute to effects on oystercatcher populations, particularly by indirect fishing mortality of undersized cockles, and that effects on other shorebird species are unknown, but likely to be small. It will be important to substantiate this last assumption.

Finally, it is worth noting the distinction between the effects of cockle harvesting, ie removal of cockles for human consumption, and the effects of suction dredging *per se*. The focus of this report is on the second aspect: the relevant effects are mortality of undersized cockles and modification of sediments and benthos. As described in Section 6.3, fishery management may be effective in preventing or mitigating these effects. With regards to direct removals of cockles, the behaviour-based modelling approach of Stillman and others (2003) is effective in determining effects on bird populations, and this approach can also be used in a predictive context (Durell and others 2005b).

4.7 Applicability to current dredging operations in The Wash

Similar to impacts on cockles (see Section 3.4), the effects of suction dredging on sediments and non-target biota are specific to gears and, particularly, sites. Gear-specific differences are slightly the less important, although clearly it would be foolish to extrapolate conclusions from studies of, for example, hydraulic dredging of razor clams in subtidal environments, or even from studies of tractor dredging of cockles in estuaries. This is partly because conclusions from studies particularly of benthic communities are necessarily rather 'broad-brush' – complex, multivariate responses require complex, multivariate analyses to extract broad signals from the data. Also, unlike the effects on cockles (Section 3.1), we are unable to determine the contributions of each stage of the dredging process. Thus, whilst we might assume that a modern solids pump dredge might be less damaging to bycatch of benthos than an older Venturi dredge, there is absolutely no evidence either to support or refute this assumption. Ens and others (2004b) noted that there was no evidence that cockle fishing operations in the Wadden Sea were less damaging recently than in previous years. Thus, given comparable environmental conditions, we take any previous study of cockle suction dredging impacts on sediment and non-target biota to be relevant to The Wash. For example, work by Moore (1991) and Cook (1991) in Traeth Lafan and Blackshaw Flats provides results that shed light on likely impacts in The Wash.

The proviso 'given comparable environmental conditions' is an important one. The main generalisation that has emerged from studies in other areas is that suction dredging impacts on benthic environments and communities are much greater in sheltered areas with muddy sediments (high silt content) than in exposed areas with sandy sediments. This results from the more dynamic nature of the environment and communities in the more exposed locations. Based on the available evidence, most of the areas where suction dredging occurs in The Wash appear to be at the sandy, exposed end of this spectrum, although there are also some more sheltered areas that support cockle fishing in some years. Despite the validity of this generalisation, it is also clear that there are many imponderables about differences between sites and even between years. For example, unseen microbial activity may play an important role in sediment stabilisation, but this would not be apparent from a purely sedimentological analysis. These imponderables make it more difficult to make predictions about likely impacts in The Wash. In each of the above sections we have taken care to relate the available evidence to the specific conditions in The Wash. We believe that our main conclusions about The Wash are sound, based on the available evidence, but it will be important to confirm this in an experimental context.

Table 4.1 The presence of cockles in intertidal biotope types of The Wash, based on Yates and others (2002). Data on biotope frequencies in 1998 and 1999 are read by eye from Figure 3.2.30 of that report; information on occurrence of cockles is taken from Section 3.2.2 of that report.

MNCR Code	Biotope name	% frequency of biotope type		Occurrence of cockles
		1998	1999	
LGS.AP	Burrowing amphipods and polychaetes in clean sand shores	9	8	absent
LGS.Lan	Dense *Lanice conchilega* in tide-swept lower shore sand	0	1	present
LMS.Pcer	Polychaetes and *Cerastoderma edule* in fine sand or muddy sand shores	18	9	abundant (commercially viable)
LMS.MacAre	*Macoma balthica* and *Arenicola marina* in muddy sandy shores (national type)	30	20	common
LMS.MacAre1	*Macoma balthica* and *Arenicola marina* in muddy sandy shores (Wash variant, lower silt)	14	23	low density or absent
LMS.MacAre.Mare	*Macoma balthica*, *Arenicola marina* and *Mya arenaria* in muddy sand shores	3	1	abundant
LMU.HedMac	*Hediste diversicolor* and *Macoma balthica* in sandy mud shores	0	1	present
LMU.HedMac.Are	*Hediste diversicolor*, *Macoma balthica* and *Arenicola marina* in muddy sand or sandy mud shores	2	2	common
LMU.HedMac.Pyg	*Hediste diversicolor*, *Macoma balthica and Pygospio elegans* in sandy mud shores	21	32	low density
LMU.HedMac.Mare	*Hediste diversicolor*, *Macoma balthica* and *Mya arenaria* in sandy mud shores	4	2	common

Table 4.2 Changes in invertebrate density in The Wash between 1986, 1998 and 1999, from Yates and others (2002). Only the statistically significant pairwise changes are shown. NB Suction dredging in The Wash did not start until after 1986.

	Change in mean density[1]		
Species or group	1986 *vs* 1998	1986 *vs* 1999	1998 *vs* 1999
Phyllodocidae		-70%	-45%
Hediste diversicolor	-51%		
'other' *Nephtys* spp.		-68%	-53%
Cirratulidae	+76%		
Arenicola marina casts	-60%	-40%	
Urothoe spp.	-85%		
Bathyporeia spp.		-70%	-54%
Corophium arenarium 3+ mm	-99%	-97%	
Corophium volutator 3+ mm			+129%
Crangon crangon	-66%	-59%	
Carcinus maenas		-83%	
Hydrobia ulvae 3+ mm		-48%	-76%
Retusa obtusa 3+ mm			-77%
Cockle 4-10 mm		-35%	
Cockle 16-40 mm			+438%
Cockle 20-30 mm	-60%		+433%
Macoma balthica <9 mm	-92%	-81%	
Macoma balthica 6-15 mm	-51%	-37%	
Macoma balthica 9-20 mm	-73%	-67%	
Mya arenaria	-97%	-99%	

[1] Change in mean density is calculated as 100 × (Density2 - Density1) / Density1, ie a change of -25% means a decrease of 25% from the starting density and a change of +25% means an increase of 25% from the starting density.

5 Comparison with other fishing methods

In this section we consider how the impacts of cockle suction dredging differ from those of other methods of cockle harvesting practised in the UK. Extraction of cockles from the sediment by 'blowing' with boats' propellers was previously practised in The Wash and Thames Estuary (see Section 2.1), but has been completely superseded by suction dredging. Most of the UK cockle landings taken from outside these two areas are taken by hand gathering. This principally occurs in the Burry Inlet, but there in some years the hand gathered cockle landings from north-west England can eclipse all other UK landings in importance (eg from Morecambe Bay in 2003). Hand gathering has continued at a low level in The Wash over recent years. Tractor dredging once accounted for much of the cockle harvest from north Wales and north-west England, but is no longer significant.

As noted in Section 3.2, one of the most important impacts of any method of cockle harvesting is that it removes commercially sized cockles from the stock. This has implications for stock dynamics, though not necessarily negative ones (Dare and others 2004), and may affect food supplies for birds (Section 4.6). These effects are common to all harvesting methods, although the choice of method will affect the ease with which a given catch quantity is taken and the likelihood of it being achieved. The focus of this section is not on this direct impact, but on how the indirect consequences for cockles and their environments differ between methods of fishing.

5.1 Hand gathering

Several methods of hand gathering have been practised in the UK and elsewhere. In the Dutch Wadden Sea, the 'wonderklauw' (magic claw) was used for centuries (Ens and others 2004b). This consisted of a rake with a net attached, and was used by fishermen wading in shallow water. In Morecambe Bay, the traditional method is to use a 'craam' to rake cockles out of the sediment (Franklin, 1972). This is a narrow three-pronged metal fork, 45 cm long, that enables cockles to be exploited at very low densities. A 'jumbo' may also be used in Morecambe Bay – this is a wooden frame which is rocked on the sand, causing it to be fluidised, bringing cockles to the surface where they can easily be gathered. A form of hand dredge was formerly used in the south Wales fisheries, but it was banned in 1969, having been found to be very damaging to young cockles (Franklin, 1972). Currently a short rake is used, similar to a garden rake, with head width up to 30.5 cm and no more than 2 cm between the tines. Cockles are raked into piles before being sieved *in situ*. This is the most generally used method, and is the only method for which there is any information about likely impacts. It will be assumed that raking is the only method of hand gathering that is likely to be practised in The Wash, and the term 'hand raking' will be used synonymously with 'hand gathering'.

Hand gathering is usually assumed to be the least damaging method of harvesting cockles in terms of impacts on sediment, benthic communities and the cockles themselves. Studies of mortality in dredge rejects (see Section 3.1) have used samples of hand gathered cockles as an experimental control (eg Franklin & Pickett, 1978; Mander & Trundle, 2001), intended to allow separation of background mortality from treatment effects. Franklin & Pickett (1978) reported that all cockles in a hand raked sample were in good physiological condition, as measured by siphon extrusion and pumping rate, and 100% survived over the course of ten days. This compared with much poorer physiological condition and survival in suction dredged (Venturi) cockles and slightly lower survival in blown cockles (Table 5.1).

In practice, hand gathering probably causes at least some additional mortality of cockles. Very few cockles attempt to re-burrow if left on sand that has drained or when there are strong drying winds (Coffen-Smout & Rees, 1999). There is at least anecdotal evidence that oystercatchers will feed on undersized cockles exposed by hand raking. However, predation of these discards should be set against the cockles that would have been preyed upon anyway, so that it is doubtful that this represents truly additional mortality. In a study involving experimental hand raking of cockles in the Dee Estuary, Kaiser and others (2001) presented evidence that damage rates of undersized cockles immediately after raking were up to three time higher in raked than in unraked areas. The level of damage was not specified, and it is not known how typical this is of commercial hand raking operations, but these results do suggest that hand raking has the potential to inflict at least some level of indirect fishing mortality on cockles.

Kaiser and others (2001) also examined changes in the sediment and benthic communities following experimental hand raking. Silt and clay content (particle sizes <63 µm) was very low (4-7%), and appeared to be unaffected by raking. This might be expected, since hand raking occurs whilst the sediment is emersed, meaning that disturbed particles are not immediately carried away in suspension. Organic matter was slightly higher in the raked areas after raking, but there were no consistent patterns. No relationship was detected between sediment particle size or organic content and benthic community composition. Differences between control and raked plots were detected in juvenile cockles, *Hydrobia ulvae*, *Corophium volutator* and the total number of individual invertebrates. No effect of raking was detected for *Macoma balthica*. Invertebrate numbers tended to be higher in the raked plots than the control plots, but this was also true on day 1 of the experiment, before raking would have had any effect. Changes between day 1 and day 14 indicated greater decreases in invertebrate abundance in the raked than in the control plots. Differences in community composition were detected between control and large raked plots up to eight weeks after raking, but the community in smaller raked plots was indistinguishable from the control by this time. No effects were detected over a year later. Kaiser and others (2001) concluded that larval settlement during the summer following the experiment, and natural perturbations during the winter had altered the small-scale patchiness of the habitat that led to the initial community differences.

It is hard to generalise from the results of a single study, but Kaiser and others (2001) do highlight that recovery rates are likely to be very variable according to sediment type and frequency of harvesting. We conclude that hand gathering in The Wash would be likely to have local effects on benthic communities similar to those expected after suction dredging. It may be significant to note, however, that unlike suction dredging, hand gathering appears to have no impact on populations of *Macoma balthica*. Given the size of the intertidal area and the likely scale of operations, hand gathering would probably have no more than very local effects. According to Dare and others (2004), the minimum viable density for commercial hand gathering is around 300 commercial cockles per m^2 for hand gathering, compared with 50-100 per m^2 or sometimes even as low as 10-20 per m^2 for suction dredging. Hand gathering operations are thus likely to be far less extensive than suction dredging. Overall we conclude that hand gathering is much less damaging to undersized cockles than suction dredging, and that the benthic impacts would probably be limited by virtue of the likely small scale of operations.

Unlike other methods of cockle fishing, hand gathering involves the presence of fishermen in intertidal areas when they are exposed, potentially disturbing feeding birds. Provided that the spatial scale of hand gathering operations is fairly small, and particularly if gathering occurs outside the periods when overwintering shorebirds are present in large numbers, the potential for disturbance is probably low. Ongoing bird-disturbance studies by CEH may shed further light on this potential. Anecdotal evidence from the Burry Inlet suggests that at least oystercatchers may become habituated to the presence of fishermen, so that losses of feeding opportunities are minimal.

5.2 Blowing

The impacts of blowing are of fairly academic interest, since it is unlikely that this method of fishing will ever be practised again in The Wash or elsewhere. In this method of fishing, also called ‘ploughing-out’, the fishing vessel was anchored over the target area in 2-3 ft of water and driven in circles (Franklin & Pickett, 1973, 1978). The anchor rope was drawn in at intervals to decrease the radius of the circle. The draught from the propellers blew the cockles out of the sand into a large central pile. At low tide the cockles were then manually sieved *in situ*, and the discards returned to the sand. Blowing was the first method of mechanical harvesting adopted in The Wash, starting in 1970 (Dare and others 2004). The method was gradually phased out as suction dredging grew in importance from the late 1980s onwards.

Franklin & Pickett (1978) showed that blown cockles were in comparable physiological condition to hand gathered cockles, and showed only slightly elevated mortality (Table 5.1). Blowing was considered to cause less damage and mortality than suction dredging because the cockles did not undergo the buffeting that occurred in the delivery pipe of the Venturi type dredges (see Section 3.1). Franklin & Pickett (1978) observed successful spatfall in areas of The Wash disturbed by blowing, although they were unable to obtain comparable data for undisturbed areas. Spatfall was only reduced in the shelly area in the centre of each blowing ring. Monitoring of stock abundance in areas affected by blowing showed that fishing did not affect the long-term potential recruitment to the fishery.

There are no data on the impacts of blowing on benthic communities, but we may assume that the impacts are likely to be at least as great as those resulting from suction dredging, and possibly much greater. Franklin & Pickett (1978) reported that the initial physical disturbance from blowing in The Wash appeared to be much more serious than that caused by suction dredging. Much of the sand surface was removed, exposing the underlying anoxic layer. Sand was removed to a depth of 12 cm or more, which compares with 4-5 cm depth of penetration for suction dredging. Infilling with sediment reduced the depth of blowing marks to 5 cm within two months. No difference in sediment height was apparent after eight months, but the rings caused by commercial blowing were still visible from the air well over a year after fishing had ceased.

We conclude that, although blowing appears to be potentially less damaging to undersized cockles than suction dredging, the probable effects on the benthic environment are likely to more than outweigh this benefit. Dare and others (2004) suggest that the minimum viable density for commercial harvesting is about 100 commercial cockles per m^2 for blowing, which is somewhat higher than for suction dredging, but much lower than for hand gathering.

5.3 Other mechanical harvesting methods

Mechanised dredging was introduced into the Wadden Sea fisheries in the 1950s (Ens and others 2004). These were essentially similar to suction dredges, but had to be emptied on board the vessel. These dredges were superseded by continuous delivery suction dredges by the late 1970s. There is no specific information on the impacts of these dredges, but it is likely that the impacts were similar to those caused by suction dredges. Some of the impacts described by de Vlas (1987) occurred after fishing with this type of dredge (see Section 4.5).

Tractor dredgers were used to harvest cockles mainly in north Wales and north-west England from the mid-1980s up to the mid-1990s. Their use extended to southern Scotland and northern Ireland during the 1990s, but the method is currently prohibited in the UK. The dredgers were essentially modified potato harvesters towed across wet sand by a tractor. An inclined horizontal blade was used to cut into the sediment, lifting sediment and cockles onto a conveyer belt from where they were carried into a large rotary riddle for sorting (Cotter and others 1997). Tractor dredging trials were carried out in the Burry Inlet by Cotter and others (1993, 1997). Relatively low damage rates were observed in the catch (average 9% for ages 2+, range 0-22%), pre-recruits (average 6% for age 1, range 0-11%) and spat (average 9%, range 0-17%). Ferns and others (2000) used data from Cotter and others (1997) to show that damage rates of undersized cockles differed according to sediment type – average 10% in muddy sand compared with 6% in clean sand. Despite the relatively low damage rates, appreciable numbers of undersized cockles were lost from the fished areas after dredging (9-19% of age 1, 30-33% of spat). Cotter and others (1997) suggested that this might be due to bird predation or tidal transport of rejected cockles. Huggett (1992) cited unpublished data (W. Cook, NWNWSFC) showing that damage occurred to cockles in the tracks of the tractor wheels (1% of small cockles, 10% of large cockles) as well as in the dredge path (2% of small cockles, 0% of large cockles). Cotter and others (1997) noted reduced spatfall in the year following dredging in a lightly dredged part of the study area. It is doubtful that this effect can be attributed to dredging, since spatfall in a more heavily dredged area was slightly higher than in undredged areas. Cotter and others (1997) concluded that there were no impacts of tractor dredging on cockles beyond the initial direct and indirect fishing mortality.

Ferns and others (2000) report on the results of invertebrate sampling that was undertaken alongside the Burry Inlet tractor dredging trials. The dredging resulted in considerable loss of invertebrates in both muddy sand and clean sand. The most affected species in the muddy sand was *Pygospio elegans*, and numbers of this species and *Hydrobia ulvae* remained depleted for over six months. Significant depletions were also observed in *Nephtys hombergi*, *Scolopos armiger* and *Bathyporeia pilosa*, but recovery was observed in less than two months. The amphipod *B. pilosa* was the most heavily depleted species in the sandy areas, but recovery was observed within less than six weeks. Other abundant species in the sandy areas had recovered within eight days. Ferns and others (2000) also recorded changes in the activity of gulls and wading birds in the dredged areas – there were initial increases in activity due to predation of organisms exposed or damaged by the dredging, but in the heavily affected muddy areas this was followed by decreased activity for up to 80 days. The authors concluded that tractor dredging causes sufficient mortality of non-target invertebrates that it should be excluded from areas of conservation importance for birds or other organisms.

Hall & Harding (1997) compared effects on benthic communities in Auchencairn Bay between tractor dredging and suction dredging. Suction dredging caused immediate impacts on some species of invertebrate, but few differences in community structure were observed after a week and recovery appeared to be complete within eight weeks (see Section 4.5). Fewer changes were attributable to tractor dredging, but the data were somewhat hard to interpret against a background of general seasonal decline in invertebrate abundance. The authors concluded that no distinction could be made between the two harvesting methods in terms of their effects on non-target organisms.

Based on the available studies, we conclude that impacts on cockles and non-target benthos are at least as great for tractor dredging as for suction dredging. Initial damage to cockles appears to be lower after tractor dredging, but this does not appear to be realised in terms of lower indirect fishing mortality. As for suction dredging, benthic impacts appear to be greater, and recovery times longer, in muddy than in sandy sediments. It may also be relevant to note that access of tractors to the shore may potentially cause environmental impacts in some areas. These conclusions are probably somewhat academic with respect to The Wash, since problems of access to the main cockle beds are likely to prevent tractor dredging from being considered, even if this method of fishing was permitted.

Table 5.1 Physiological condition and survival of cockles taken by three different methods. data from Franklin & Pickett (1978).

	Harvesting method		
Condition measure	**Hand raked**	**Blown**	**Suction dredged**
Recovery (siphon extrusion)	100% (15 min)	100% (15 min)	25% (100 min)
Pumping rate of 'recovered' cockles (absorption of methyl red over 3 h)	100%	100%	30%
Survival over 10 days	100%	100%	100%

6 Mitigating measures

The foregoing sections have reviewed the available information on how suction dredging for cockles impacts on the cockles themselves, their environment and on the organisms with which they share living space. In some cases it has been made evident that impacts could be reduced or eliminated by changing or managing fishing practices. In this section we review the likely ways in which this could be achieved.

6.1 Gear design

The most obvious example of changes in the design of suction dredge gear that have reduced the impact has been the change from the original Venturi pump dredges to the modern solids handling pump dredges (Section 2.1). Damage rates to both commercial and undersized cockles have been reduced because the modern system causes much less buffeting of cockles in the dredge delivery pipe (Section 3.1). There is no hard evidence either way, but we assume that modern solids pump dredges are also less damaging to non-target organisms taken as by-catch, or at least are no more damaging. Many changes to the technical specifications of the gear are made by fishermen for sound commercial reasons – reduced damage rates in the retained catch mean improved quality and value in the processed product

– and such improvements also imply less damage to the discarded portion of the catch. It should also be emphasised that fishermen are the first to recognise that their future livelihood depends on the survival and growth of cockles which are not yet recruited to commercial size. Several aspects of gear design may influence the amount of damage caused by suction dredging operations:

- the relative amounts of work done by the dredge blade and the digging jets in guiding cockles into the dredge head;
- the choice of slots or holes for the digging and separating jets;
- the pressure and direction of jets and their total outlet area;
- whether or not a blade is fitted to the dredge, its width, angle, depth setting and cutting edge;
- how much sorting is performed at the dredge head, presumably dependent on the spacing of grid bars;
- the use of either a rigid or a flexible delivery pipe;
- the bore and smoothness of the delivery pipe, and whether or not it has sharp bends;
- the design, size and operating pressure of the solids handling pump;
- the way in which the cockles are delivered into the deck riddle;
- the rotation speed of the riddle;
- the bar design of the riddle, and whether or not rubber sleeves are fitted to the bars.

Many of these aspects of gear design are under constant review by fishermen and gear technologists (eg Hopper, 1986). For example, new pumps are constantly tested as they become available on the market (see Sections 2.2 and 3.1), and it may be assumed that damage caused by the pumps has declined and will continue to decline over time. Too few data are available to allow us to comment on individual aspects of gear design and how they might influence dredge impacts. However, management measures such as the enforcement of maximum breakage rates should continue to provide incentives for gear improvements that provide benefits for both commercial interests and the wider environment. In Section 3.1 we highlighted selection at the dredge head as one of the least understood aspects of the dredging process. For the full benefits of gear improvements to be both realised and measured, it is vital that an improved understanding be gained of what happens during this hidden stage of the dredging process.

6.2 Fishing operations

The updated handbook on the original White Fish Authority dredge (Siddle, 1988) contains guidance on the correct operation of dredges to avoid damage to cockles and other problems. This guidance is here reproduced in Tables 6.1 and 6.2. Although it refers to the early Venturi design of dredge rather than modern solids pump dredges, the same general principles apply. Much of the guidance is common sense operational procedure, such as not operating dredges at too great a depth or towing at too great a speed. This represents best practice, rather than something that can be laid down prescriptively by managers. However, enforcement of measures such as maximum breakage rates can act as strong incentives for good practice. The 10% maximum breakage rate currently in force in The Wash Fishery Order is clearly achievable, although not every fishing vessel demonstrates this standard on first testing. Mander & Trundle (2001) reported that one vessel which failed to meet the required standard after being tested three times in 2001 was finally awarded a certificate of approved gear after changing parts of the fishing gear.

6.3 Fishery management

Many different management measures are in place for cockle fisheries around the UK and elsewhere. These include limited entry licensing, daily catch quotas and Total Allowable Catch (TAC) levels, minimum legal sizes (MLS), gear specifications, maximum breakage rates and others. The management tools available, and the purposes for which they are used are summarised by Dare and others (2004). Management objectives are often not stated explicitly, but broadly the purpose of current management is to limit the impact of fishing on the targeted stock, ie stock conservation. The aims are to ensure that there are sufficient spawners to allow the stock to replace itself, and to conserve stock biomass for future exploitation. Concepts such as Maximum Sustainable Yield (MSY) are not generally applied to cockle stocks, partly because their management has of necessity evolved in an *ad hoc* fashion, based on experience rather than a conceptual framework, but also because the highly dynamic and often unpredictable nature of changes in cockle stock abundance are often outside direct fishery control. For example, Bell and others (2001) found that fluctuations in cockle stock abundance in the Burry Inlet were largely controlled by levels of spatfall success, and this may well be true of other stocks. Cockle spatfall in The Wash appears to be controlled by environmental and density-dependent factors, without being limited by the production of larvae (Young and others 1996, 1998; Dare and others 2004). However, survival to recruitment appears to be a crucial factor determining the size of the commercial stock in The Wash, and management may have a role to play in influencing this process (see below).

Management of cockle fisheries in England and Wales is under the control of Sea Fisheries Committees (except in the Dee Estuary, where this responsibility falls to the Environment Agency). Their remit has largely been limited to management for purely fishery objectives, as described above. Where sites receive designations for their high conservation value, for example under the Birds or Habitats Directives, additional responsibilities arise for conservation managers. These would include maintaining the interest features of the site in favourable status. It is, of course, up to the responsible bodies, in partnership with other managers and stakeholders, to determine the direction that management should take. Inevitably, this will involve setting out management objectives for cockle fisheries which go beyond sustainable management of the stock itself. It is important that these objectives be stated clearly, and that clear criteria for ‘favourable status’ be defined, against which management outcomes can be measured. We do not attempt to pre-judge these objectives or criteria in this report. Rather, we set out some of the management tools that are available, considering how they can be used to influence the effects of suction dredging on stocks, non-target organisms and the environment.

A necessary precondition for many relevant management measures is a limited entry licensing system. This is in place in The Wash, and allows *inter alia* the setting of harvest limits and spatio-temporal controls on fishing effort. In the following discussion of management possibilities we will assume that such a licensing system is in place, and will not consider it further as a management tool in its own right.

Harvest levels

In regulated cockle fisheries it is common to define upper limits for the quantities (weight) of cockles allowed to be taken within a given fishing season. These are generally calculated as proportions of the biomass of exploitable cockles estimated in pre-season stock surveys. This is true of cockle fishery management in the Thames Estuary, Burry Inlet and The Wash. A rule-of-thumb for sustainable management of cockle fishing was derived for the Burry Inlet, based on the observation that harvest levels over a sustained (and therefore presumed sustainable) period of exploitation were in a range extending up to about a third of the takeable stock. Bell and others (2001) provided some evidence that there was a biological basis for this threshold: once the effects of oystercatcher predation are accounted for, this appears to be within the capacity of the population to compensate by reductions in mortality from other (unknown) sources (see Section 4.6). Similar harvest levels have been set for other cockle fisheries (eg Thames and Wash), although it is unknown whether the same compensatory principle applies at these sites. Draft cockle fishery management policy for The Wash (ESFJC) is for a TAC of 30% of the estimated takeable stock biomass, but combined with a precautionary minimum stock biomass for fishing and a sliding scale of reduced harvest levels between this minimum biomass and a higher threshold. Although the thresholds and harvest levels are (necessarily) empirical rather than being a rigorously estimated set of biological reference points, this general policy does appear to offer a flexible and precautionary framework for managing to both fishery and conservation objectives (see below). Daily catch quotas are often imposed in addition to overall TACs. This is primarily an operational rather than scientific issue, but it may be relevant to note that the duration and intensity of fishing activity conceivably could have some bearing on possible management objectives.

Harvest limits for cockle fisheries are equally applicable to any method of fishing. The obvious purpose of harvest limits is to conserve the stock (see above), but clearly they can also be used to set aside stocks for other purposes. Before the current closure of the Wadden Sea cockle fisheries, TACs were set with reference to the food requirements of shellfish eating birds. Cockle and mussel stocks corresponding to 60-70% of the estimated food requirement of a reference number of birds (corresponding to average levels in the 1980s) were set aside (Common Wadden Sea Secretariat, 2002). The cockle fishery was closed when the total stocks failed to meet this requirement. As described in Section 4.6, a food reservation policy does not automatically guarantee sufficient food supplies for oystercatchers or other shorebirds. It should also be emphasised that in this context cockles cannot be considered in isolation from mussels. Thus, for example, relaying of mussels in intertidal areas of The Wash could have a bearing on cockle fishery management.

The focus of this report is suction dredging. The only aspect of harvest limits that is specifically relevant to suction dredging is the consideration that limits for the commercial harvest also imply limits for the indirect fishing mortality inflicted on undersized cockles. Deliberately, very little has been written in this report about the rejection rate of cockles. This is because they are immensely variable, and depend entirely on the composition of the stock in relation to the minimum commercial size. We know that indirect fishing mortality of pre-recruit cockles may be significant (see Section 3.3), but what this means in numerical terms depends on the size-composition of the stock in the dredged areas. If dredging is limited to areas of mainly commercial cockles, then relatively few cockles will be rejected. Dredging-induced mortality of the cockles in this dredged area may be significant **at that location**, but in total stock terms may well be negligible. If, on the other hand, commercial cockles are extracted from beds of mainly undersized cockles, the mortality may well be significant at more than just the local scale. Clearly, this is an aspect of fishery impacts that is susceptible to management by spatial controls (see below). This is likely to form the most important tool for constraining indirect fishing mortality on pre-recruit cockles, but harvest limits may have some role to play in circumstances when there is not a clear spatial separation between commercial and undersized cockles.

Spatial and temporal management

As stated above, the most obvious reason to place spatial controls on cockle fishing in The Wash is to exclude dredging from areas where significant damage may be caused to undersized cockles. As highlighted by Dare and others (2004), it is not clear whether the low survival to recruitment of cockles in The Wash is a recent phenomenon, possibly attributable to dredging, or is a natural feature of cockle stocks in this area, ie a context for management rather than a process susceptible to management control. Whatever the case, and it may be a combination of the two possibilities, any management measure that minimises the additional mortality to pre-recruits is to be welcomed. Already, it is common practice for cockle fishing in The Wash to be excluded from areas of primarily undersized cockles.

Temporal management is also currently applied in The Wash. There is currently a short summer season for cockle fishing, and this is also constrained by the quantity of the available harvest and the time taken to remove it. The summer season avoids disturbing spawning cockles, and also ensures that the cockles are in their best condition – this is a commercial benefit, but also means that the fewest cockles are taken for a given catch weight. Several other reasons exist for constraining the times and places that fishing might occur in The Wash. It would be pure speculation to suggest how effective any particular measure might be for any given management objective, but possible reasons for applying spatial and temporal controls include:

- excluding fishing from muddier areas, where impacts on the sediment and benthic invertebrates would be expected to be greatest;
- excluding fishing from areas that might act as a focus for mussel settlement, which might include areas of dense *Lanice* tubes;
- excluding fishing from areas of primary importance to feeding shorebirds and where dredging may be expected to affect the food supply by damage to cockles or non-target benthos;
- restricting fishing activity at times when this might increase the vulnerability of particular areas to natural erosion from storms or tides;
- encouraging fishing in stock areas that may be particularly vulnerable to loss from storms.

Any or none of these may be sensible reasons for spatial and temporal controls in any given circumstances, but this gives a general impression of how these controls might be used.

Technical measures

Technical measures for cockle fishery management include minimum legal sizes (MLS), maximum breakage rates and gear specifications. Maximum breakage rates, currently set at 10% for a sample of retained catch and discards combined (Mander & Trundle, 2001) have already been discussed above in relation to gear design and fishing operations (Sections 6.1 and 6.2). Clearly, they can be a strong incentive towards good practice, thereby helping to constrain the amount of additional fishing mortality inflicted on pre-recruit cockles.

The application of a cockle MLS would also appear to constrain the mortality inflicted on smaller cockles, and to allow cockles to spawn before being harvested. However, there is a strong counter argument to this. If cockles stand an appreciable chance of being killed in dredged areas, by being rejected as undersized, then any measure which increases the numbers of cockles classed as undersized will have the effect of transferring cockles from the retained catch, where they are counted against any quota or TAC, to the rejected portion of the catch, where they add to the indirect fishing mortality. Draft ESFJC policy is to have, instead of a cockle MLS, an upper limit on the level of discarding allowed at the riddle. Thus, if fishing kills a cockle, it is much more likely to count towards the harvest limit. Although this should not be regarded as an alternative to spatial controls, the introduction of a discard limit is likely to have the effect of excluding fishing from areas dominated by small cockles. Faced with ground containing many small cockles, fishermen would have two choices: either to accept a large proportion of small cockles in the catch, which might reduce its value; or to fish elsewhere where commercially acceptable cockles predominate. It is yet to be seen how effective this policy will be in practice. Two possible dangers are: (i) that markets might develop for small cockles; and (ii) that there may be pressure to increase the unseen discarding at the dredge head, where mortality is possibly higher than at the riddle (Section 3.1).

A variety of other technical measures are already in place. These include restrictions on the number and width of dredges to be used. As noted above (Sections 6.1 and 6.2), technical developments in the fishery towards less damaging gear can perhaps be left to the fishermen themselves, as improvements that are of commercial benefit are also likely to carry other benefits. Over-prescriptive management for gear specifications runs the risk of stifling potentially beneficial gear developments. Nevertheless, some awareness is also needed of any possible conflicts between the commercial and the wider benefits of any particular gear developments.

Table 6.1 Dredge malfunctions and corrective actions, taken from the updated handbook on the White Fish Authority dredge (Table 2 of Siddle, 1988).

No.	Malfunction	Corrective action
1	Dredge tipped over on side.	Raise off bottom and drop, or raise to deck level and check for malfunctions 2 and 3.
2	Suction unit blocked.	Raise dredge to deck level and check for weed, driftwood, bottles, stones, polythene sheet, *etc.*
3	Choked with sand or mud.	Raise dredge and check. The rouble has often cleared by the time the dredge reaches the surface. Check blade depth is not excessive, the pump pressure is adequate and the jet pipes are in order.
4	Lifting off bottom as a result of excessive depth or towing too fast, especially against strong tide.	Reduce towing speed. If trouble persists check depth of water. If over 4.5 m it is unlikely that dredging can be continued. However, a slower towing speed and weights on the dredge may improve efficiency.

No.	Malfunction	Corrective action
5	Towing light at front end and not taking full depth of cut.	Raise and examine shine on bottom of runners. If balance of dredge has altered add weights to front of dredge. If not, condition caused by onset of malfunction 4.
6	Partially towed by pipes. Rear-end raised.	Raise and examine for shine at front end of runners. This indicates pipe lengths too short for chain length. Correct by shortening the towing chain.

Table 6.2 Reasons for damage to cockles and corrective actions, taken from the updated handbook on the White Fish Authority dredge (Table 1 of Siddle, 1988) malfunction numbers refer to Table 6.1.

No.	Reason for excessive damage to cockles	Corrective action
1	Incorrect depth of cut or dredge malfunctions 4, 5 or 6.	Increase blade depth setting or correct malfunctions 4, 5 or 6.
2	Falling too far into the hold and striking floor.	Install simple chute to channel the cockles into the hold.
3	Pressure too high at pump delivery, creating too much turbulence.	Check that pump outlet pressure is normal. If damage persists and excessive chipping is also present check that sufficient water is escaping from digging and separating jets.
4	Pressure too low at dredge, allowing cockles to build up in the dredge or pipe-work.	

7 Conclusions

7.1 Nature of dredge impacts

Suction dredging for cockles has the potential to affect the cockles themselves, non-target benthic invertebrates and the sediment. In cockles, the principal effect appears to be damage and consequent mortality of undersized cockles rejected at the dredge head and at the deck riddle. Damage rates are very specific to gear set-up, operators and sites, but it seems likely that an average of about 27% additional fishing mortality in dredged areas can be inflicted on undersized cockles beyond the direct fishing mortality of the retained catch. The significance of this mortality to the stock as a whole depends on the extent to which undersized cockles co-occur with commercial cockles in the areas targeted by dredgers.

Suction dredging appears not to have strong adverse effects on cockle spatfall success in areas with naturally mobile sediments, either in the short-term, from dredging over areas of settling cockles, or in the longer-term, through effects on sediment suitability. In relatively sheltered areas, suction dredging can cause a loss of fine silts from muddy sediments. Eelgrass beds are particularly vulnerable. Cockles play important roles in promoting sediment stability and in adding fine particles to the sediment through biodeposition. The loss of these functions may exacerbate the loss of silts from muddy sediments and cause prolonged recovery times. Invertebrate communities in muddy, sheltered areas are also much more vulnerable to short- and long-term disturbance by suction dredging than communities in more exposed areas where sediments are naturally low in silt. Invertebrate communities in these exposed situations are, like their habitat, very dynamic, and dredge impacts are undetectable within days to weeks. Some concern remains, however, about the effects on the more structural components of such communities (eg polychaete tubes) and about effects on the bivalve *Macoma balthica*.

Dredging effects on *Macoma* are of interest because this species forms an alternative food resource for shellfish-eating shorebirds that also feed on cockles. This applies particularly to knot, an important predator of cockle spat. Cockle fishing has been shown to affect knot and oystercatcher populations at some sites, both through direct competition for resources (ie cockles) and through habitat modifications that affect the capacity to support the bird populations. Competition for food is only important when other food resources, such as mussels, are also in short supply. Effects through habitat modifications are mainly relevant to sheltered, muddy areas. Suction dredging may cause some loss of secondary production even from sandy areas, principally through immediate mortality of invertebrates, but these effects are probably small in scale compared with natural perturbations, particularly in sandy areas.

7.2 Current dredging operations in The Wash

There is a lack of Wash-specific studies of suction dredging effects on environment and communities, but we can draw some conclusions about likely effects from the fact that The Wash appears to be at the more sandy, exposed end of the spectrum of sites where suction dredging for cockles has occurred. For this reason, the sediments and benthic communities over much of The Wash are thought to be relatively resilient to the effects of suction dredging. Sediments in the commercial cockle beds are generally sandy, and this appears to be a natural circumstance rather than an effect of suction dredging. However, it should be noted that there are also some more sheltered areas of The Wash, with muddier sediments, where suction dredging occurs in some years. Greater impacts and longer recovery times would be expected in these areas. The same might also apply to biotopes in sandy areas where there is an important structural element (*Lanice* tubes), but this is though to be relatively unimportant in terms of commercially exploitable cockles.

Aside from the effects of direct fishing mortality of retained cockles, common to any method of fishing, the main effect of suction dredging on cockles in The Wash appears to be elevated mortality of cockles before they recruit to commercial size. Studies with dredges currently used in The Wash have shown that considerable mortality is caused to cockles rejected at the deck riddle. We infer from a study in the Thames that mortality among cockles rejected at the dredge head may be at least as high. There is some concern that this may have contributed to the low overall survival to recruitment observed in Wash cockles, although there is also evidence that, at least over the first winter, this low survival may be a natural phenomenon. Spatial management and technical measures (upper limits on breakage and discard rates) are likely to be very effective in mitigating this particular impact.

Oystercatcher populations in The Wash have been shown to be adversely affected by low abundance of cockles in years when mussel stocks have also been low. Suction dredging may have contributed to this effect by out-competing oystercatchers for commercial sized cockles, and perhaps by causing increased mortality of undersized cockles, but the importance of this effect in comparison with natural variations in cockle abundance is not known. Effects of dredging on non-target benthic invertebrates are thought not to have affected bird populations in The Wash. There are some grounds for concern that dredging may affect populations of *Macoma balthica*. This could potentially impact upon knot, for which *Macoma* is an important food source, but there is no evidence that this has actually occurred. This may be because the main concentrations of *Macoma* in The Wash are thought to be further up the shore than the cockle fishing areas.

The basic design of suction dredges used in The Wash has remained fairly stable since the introduction of this fishing method in the late 1980s. However, there is constant evolution in dredge components such as the solids handling pumps. To the extent that they are aimed at decreasing damage rates of commercial cockles in the retained catch, such developments may also carry benefits of reduced impacts on undersized cockles and non-target benthos.

Overall, we conclude that suction dredging for cockles in The Wash need not be incompatible with maintaining the features of the site that are of nature conservation importance, but note the caveats above in relation to dredging in more vulnerable areas and impacts on non-target biota with implications for important bird populations. As with any activity, suction dredging does carry impacts, but (i) there is considerable scope to manage the fishery to mitigate these impacts, and (ii) the wider biota and environment of The Wash appear to be naturally dynamic and therefore fast to recover from the impacts of suction dredging and other perturbations. These conclusions differ from those drawn from the EVA II evaluation of the Dutch shellfish fishery policy (Ens and others 2004b), on the basis of which the Dutch government ruled that the Wadden Sea cockle fishery should be closed as of 1 January 2005. However, the findings of the current report are that The Wash differs from the Wadden Sea in some important respects, and would generally be expected to be more resilient to suction dredging impacts.

7.3 Future research needs

The foregoing sections have highlighted the lack of Wash-specific data that limits our ability to draw firm conclusions about impacts of suction dredging activities on the environment, cockles and other biota. The findings of many research studies appear to be quite specific to the study sites and even to the particular dredging circumstances. Moreover, some aspects of the dredging process are poorly understood at any site. This section gathers together recommendations for future research that can be used to inform future management of suction dredging activities to the benefit of both fisheries and nature conservation. This is complemented in Section 9 by a consideration of the research questions that could be addressed using current data resources and some recommendations for future monitoring.

Dredging processes

- Rejection of cockles at the dredge head is one of the least understood parts of the suction dredging process. A single study of survival of dredge head discards in the Thames Estuary (Wiggins, 1991) has been used to infer that this stage of the process may be at least as important as rejection at the riddle. If technical measures are to be defined as part of fishery management, it will be important to understand how each stage of the dredging process contributes to the overall impact of dredging on the cockles. Thus, it will be important to undertake a new study of rejection at the dredge head that will serve to repeat and confirm (or otherwise) the results of the Thames study and to ensure that the results are relevant to current dredging operations in The

Wash. The study should address the following questions: (i) how much of the size selection of cockles occurs at the dredge head as compared with the deck riddle? (ii) what are the damage rates of cockles rejected at the dredge head, and how are these influenced by aspects of dredge head design? (iii) what level of additional mortality is inflicted on apparently undamaged cockles that have been rejected at the dredge head? As regards mortality of damaged rejects, it is probably enough to infer from recent studies of damaged riddle rejects that it is very high (eg Mander & Trundle, 2001).

- Several aspects of dredge design are subject to constant development. These include the type of pipework and the design and size of pumps. It is currently unknown how these developments affect the amount of damage inflicted by the dredges to undersized cockles. Much could probably be learned from routine monitoring of damage rates undertaken as part of the enforcement of maximum breakage rates (eg Mander & Trundle, 2001). Collection of comprehensive data on gear and operational variables alongside damage rate measurements, coupled with rigorous statistical analysis could reveal much about the sources of variability in damage rates. Although it is perhaps unlikely that this information would be used to define restrictions on the type and design of gear that could be used, it would nevertheless provide insight into the type and level of response that might be achieved by other management measures.

- Even if there was a much improved understanding of how each individual aspect of the dredging process contributes to the overall impact, this would not substitute for direct measurements of the impacted population that would reveal how the impact worked out in practice. Studies by Franklin & Pickett (1978) in the Thames Estuary provide an example of how stock monitoring was used to gain an insight into the impact of the Venturi design of dredges. The following aspects of cockle stocks should be considered in The Wash: (i) spat settlement; (ii) spat survival; (iii) survival to recruitment; (iv) *in situ* damage rates; (v) growth rates; (iv) additional mortality of commercial cockles beyond the direct effects of fishery removals. Such monitoring would be best conducted alongside commercial dredging activities rather than experimental dredging, since the former will allow for repeated impacts and realistic (because real!) operating conditions. It is nevertheless important that a rigorous experimental protocol be designed around the monitoring. This would include replication, monitoring before and after impacts and monitoring of both dredged and control plots (ie use of the before-after-control-impact or 'BACI' design, eg Smith and others 1993). To be most effective, monitoring would need to occur over an extended period, eg 2-3 years to cover the time taken for a year-class to recruit fully to commercial size.

Effects on benthos and environment

- The field study protocol described above could also be used to address questions about the impacts of dredging on sediments and non-target benthic communities in The Wash. This would involve collecting data on sediment parameters (median grain size, percentage of particles <63 μm, organic matter content, sediment shear strength, geochemical gradients), and macroinvertebrate communities. Analysis of invertebrate data will require the use of multivariate analysis techniques (eg Hall & Harding, 1998) to detect the response of community composition and structure. Beyond the BACI design, it will also be important to have continued monitoring to allow recovery times to be measured. Based on the available evidence, this would probably take under a year for most of the benthic parameters, which would probably mean that the time between fishing seasons would be sufficient. On the other hand, there may be some variables, such as the densities of *Macoma balthica*, which may need to be measured over a longer period. It may be possible, through spatial management of fishing effort, to provide for this monitoring without placing constraints on the fishery. Finally, it will be important to ensure that initial sediment parameters and invertebrate communities are as similar as possible between control and impact plots.

Ecosystem effects

- It is probably unrealistic to expect that the impacts of suction dredging on all components of the estuarine food web will be addressed in future research studies. It will, however, be important further to consider the effects of dredging on bird populations. The effects on overall Wash populations have probably been considered enough by, for example, Dare (1999), Atkinson and others (2003) and Stillman and others (2003), but there is still scope for improving our understanding about how birds interact with fishing activities at a more local scale. Extended monitoring of bird feeding activity in dredged and undredged areas would be possible alongside the BACI study outlined above. This might involve direct observations of bird behaviour in the monitored areas, but could also include the indirect measures (bird footprints) used by Ferns and others (2000). The outcome of such monitoring might be that it would be possible to determine the effect of dredging on bird-days in The Wash. This information would be highly valuable if, for example, the number of bird-days that The Wash can support was to form a target for SAC management.

It is apparent that several of the studies suggested above could be undertaken in parallel. An integrated approach to this research would be of great benefit in helping to gain an holistic understanding of the possible impacts of suction dredging in The Wash.

8 Available data on The Wash

The ecology and environment of The Wash are well studied. This section considers some of the existing data resources that might allow us to determine how suction dredging has affected cockles, other species and their environment in the past. We have not attempted to be comprehensive in this account of data resources, since Wash studies are many and various, differing in their spatial and temporal scales, and much of the data from such studies would have very little bearing on suction dredging activities. Instead, we concentrate on a few data sets that cover The Wash at a large spatial scale, but with sufficient spatial resolution to allow meaningful cross-comparison at the scale of cockle dredging activities. These data fall into three categories: (i) cockle stocks and fishing activities; (ii) invertebrate communities and sediment characteristics; and (iii) shorebird populations. Note that the data are not here described – we merely note the existence of data which could be extracted and collated at some future date.

8.1 Distribution and level of cockle fishing effort

Fishing effort data for the Wash cockle fishery are held by ESFJC for the period 1988 onwards. Up until 1992, the data relate to both suction dredging and blowing, the two data sets being separate. The current cockle fishery licence requires a weekly return of landings by each vessel, recording gear type, areas fished, daily totals landed and time spent fishing

(Figure 8.1). Twenty-eight areas of The Wash are distinguished for the recording of fishing effort (Figure 8.2).

This data set forms the basis for any meaningful analysis of suction dredging impacts in The Wash. The success of any analysis depends on the extent to which other data can be matched with the areas defined in Figure 8.2.

8.2 Distribution and population structure of cockles

Regular cockle survey data for The Wash exists for 1992 onwards (ESFJC data). There is generally a survey before the start of the fishing season (March to May) to determine the stocks available for the fishery, and an autumn survey (August to December) to determine the extent of settlement and to assess the effects of the fishery on the stock. The survey areas generally correspond with the fishing areas (Figure 8.2), although there is some aggregation in the presentation of the results (eg Jessop and others 2003). Samples consist of 0.1 m^2 areas of sediment sampled to a depth of 125 mm using a day grab. Size-classes and year-classes are recorded for each sample. Survey precision is low, owing to the very large area that is covered. In 2003 a total of about 900 samples was collected (Jessop and others 2003). The surveys allow calculation of stock biomass and structure. The surveys concentrate on the main fishable stocks, so are not fully comprehensive of the stock in any one year.

Dare and others (2004) describe various other sets of data that are available on cockle abundance in The Wash. These include historical data for The Wash presented by Franklin & Pickett (1968). These data probably are too disparate to allow meaningful integration into any analysis of suction dredging impacts, but could in some circumstances provide a useful historical context.

8.3 Sediment and benthic invertebrate communities

The most comprehensive data on the invertebrates and sediments of The Wash are from surveys by the Centre for Ecology & Hydrology (Yates and others 2002). In 1986, samples were taken at 192 sites, in 1998 samples were taken at 118 sites, 91 of which were included in the 1986 survey, and in 1999 samples were taken at 103 sites (Figure 8.3). Each site was a 1 ha block within which samples were taken. Five sediment samples were taken at each site, and the sediment particle sizes and organic matter content were measured in the laboratory. Invertebrate samples consisted of five pairs of 10 cm cores randomly located at each site, taken to a depth of 30 cm. The samples were sieved over a 0.5 mm mesh, and the retained invertebrates were identified to species. At four of the sample points, a 0.5 m square was dug over to quantify the larger, less abundant invertebrates such as cockles.

Data from these surveys are of sufficient resolution and coverage to allow the cockle fishing areas to be represented (compare Figures 8.2 and 8.3). The 1986 survey provides data before the start of suction dredging in The Wash, although mechanical harvesting in the form of blowing was taking place at that time.

Data on invertebrates and sediment characteristics are available for some intertidal stations around the Great Ouse Estuary, sampled from 1992 onwards on behalf of the Environment Agency and its predecessors (Bailey and others 1999). Most of the sampling stations fall outside the main cockle fishing areas, so that it is unlikely that this detailed data resource will provide much insight into the effects of dredging activities.

8.4 Shorebirds

The most obvious data resource on the shorebirds of The Wash is the Wetland Bird Survey (WeBS) undertaken jointly by the British Trust for Ornithology (BTO), The Wildfowl & Wetlands Trust (WWT), and the Royal Society for the Protection of Birds (RSPB) under the aegis of the Joint Nature Conservation Committee (JNCC) (eg Pollitt and others 2003). Monthly counts for The Wash as a whole are available for 1972 onwards. Counts are missing for some months in some years, but there is sufficient coverage to allow a complete picture to be constructed of bird usage within any given year or season. The counts cover all wader and wildfowl species, surveyed mainly at high tide roosts. Comprehensive analyses of recent data for knot and oystercatcher are provided by Dare (1999) and Atkinson and others (2003). The WeBS data provide an excellent overview of trends over years, but they do not provide an insight into how the birds use the sites. This is provided in comprehensive low tide surveys of shorebirds on the inner banks of The Wash by CEH (Yates and others 2004). Data are available for the winters of 1985/86, 1989/90, 1990/91, 1991/92 and 2002/03. Precise locations are recorded for individuals and flocks, where possible, but for the purposes of comparison the inner banks are divided into 75 units (Figure 8.4). For the purposes of comparison with fishing activities, it might also be necessary to create divisions up and down as well as along the shore.

8.5 Other supporting data

It is worth noting that satellite imagery (LANDSAT 5 Thematic Mapper data) have successfully been used as a substitute for sediment sampling data for The Wash (Yates and others 1993b). Satellite imagery data have the advantage that a time-series can be built up (dependent on cloud cover and the frequency of passage of the satellite over the site). Satellite imagery data are unlikely to provide insight into effects of dredging on sediments, but is conceivable that the data may prove useful as supplementary explanatory variables in analyses involving years for which there are no direct sampling data.

Meteorological data may be useful as supplementary information in various analyses. For example, temperature data can be used in calculations of daily energy budgets for shorebirds (eg Bell and others 2001). Data on wind speed and direction, air temperature, precipitation, insolation, etc are available from the Meteorological Office. Current meteorological stations are at Holbeach, Hunstanton, Wainfleet, Skegness and Kirton. Sea temperature data are available for The Wash for the years1963-73 (Jones & Jeffs, 1991). Dare and others (2004) cross-calibrated sea temperatures with air temperatures from Skegness to provide a continuous series of sea temperatures over the last century. Synoptic climate data are available from the Climatic Research Unit of the University of East Anglia. This includes summaries of atmospheric circulation patterns, as used by Young and others (1996) and Dare and others (2004) in analyses of cockle and mussel spatfall trends. The North Atlantic Oscillation (NAO) index provides a synoptic measure of major climatic trends.

WASH FISHERY ORDER 1992

LICENCE Nº: ____________

WEEKLY RETURN OF LANDINGS

VESSEL Name: .... Reg Nº:

OWNER Name: ....

Address: ....

....

Postcode: ....

Telephone Nº: ....

DAY	DATE	QUANTITY LANDED (Tonnes)	AREA FISHED (see over)	SPECIES	METHOD OF FISHING	TIME SPENT FISHING (Hours)
Monday						
Tuesday						
Wednesday						
Thursday						
Friday						
Saturday						
Sunday						

Figure 8.1 Form for recording of fishing effort by licensed vessels fishing for cockles within the Wash Fishery Order.

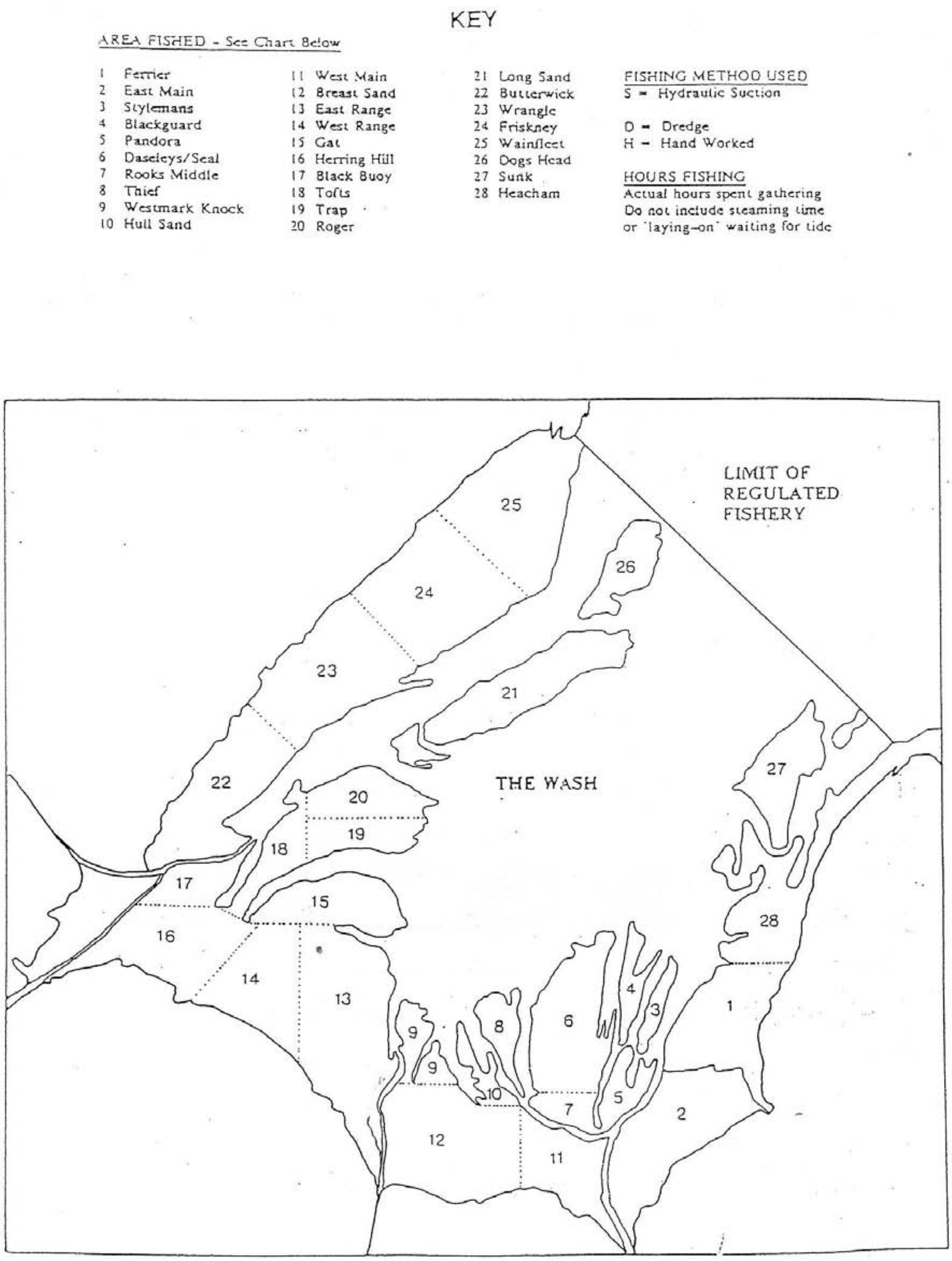


Figure 8.2 Areas for recording of fishing effort by licensed vessels fishing for cockles within the Wash Fishery Order.

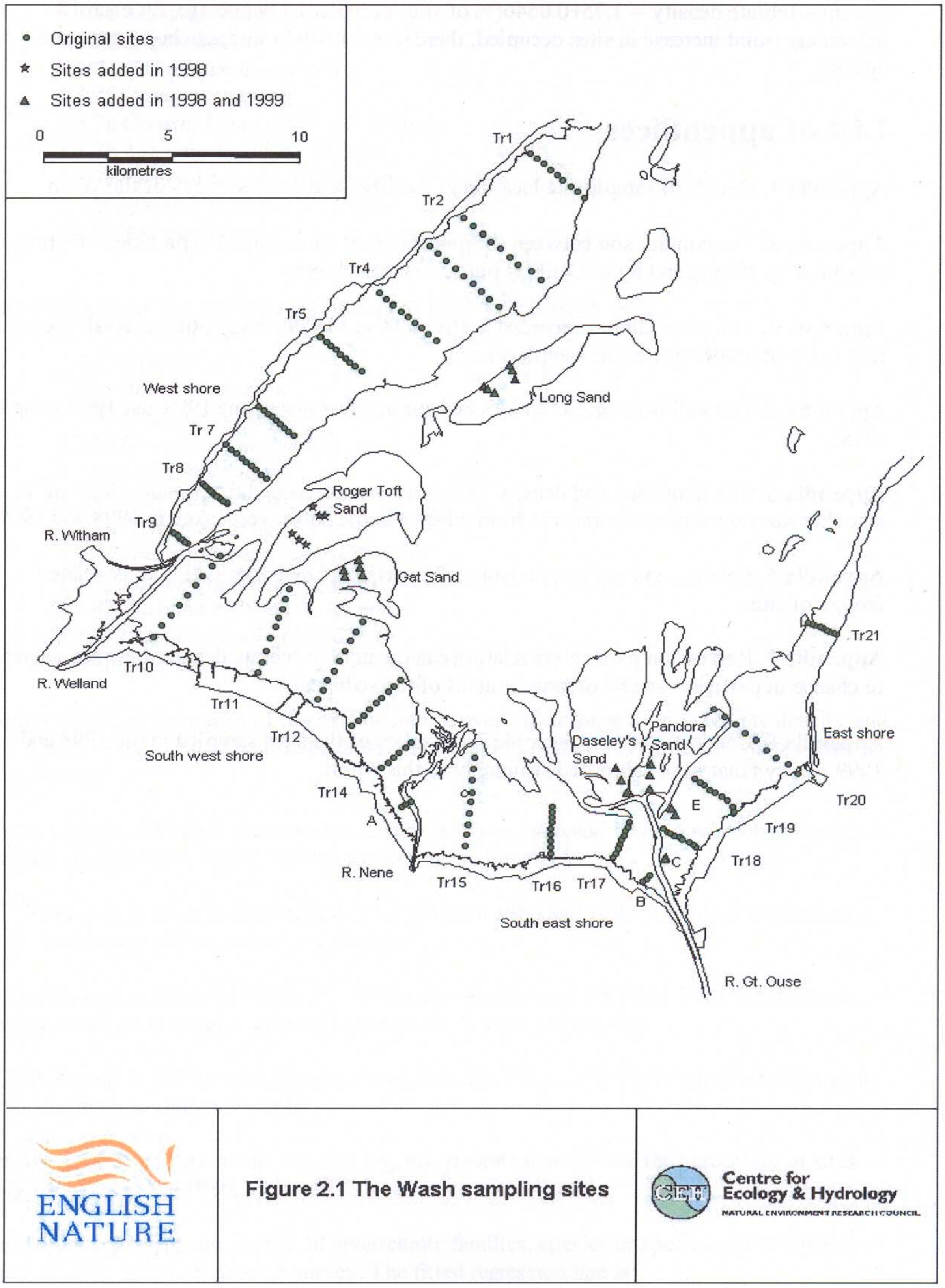


Figure 8.3 CEH sampling sites for benthic invertebrates and sediment characteristics in The Wash, taken from Yates and others (2002).

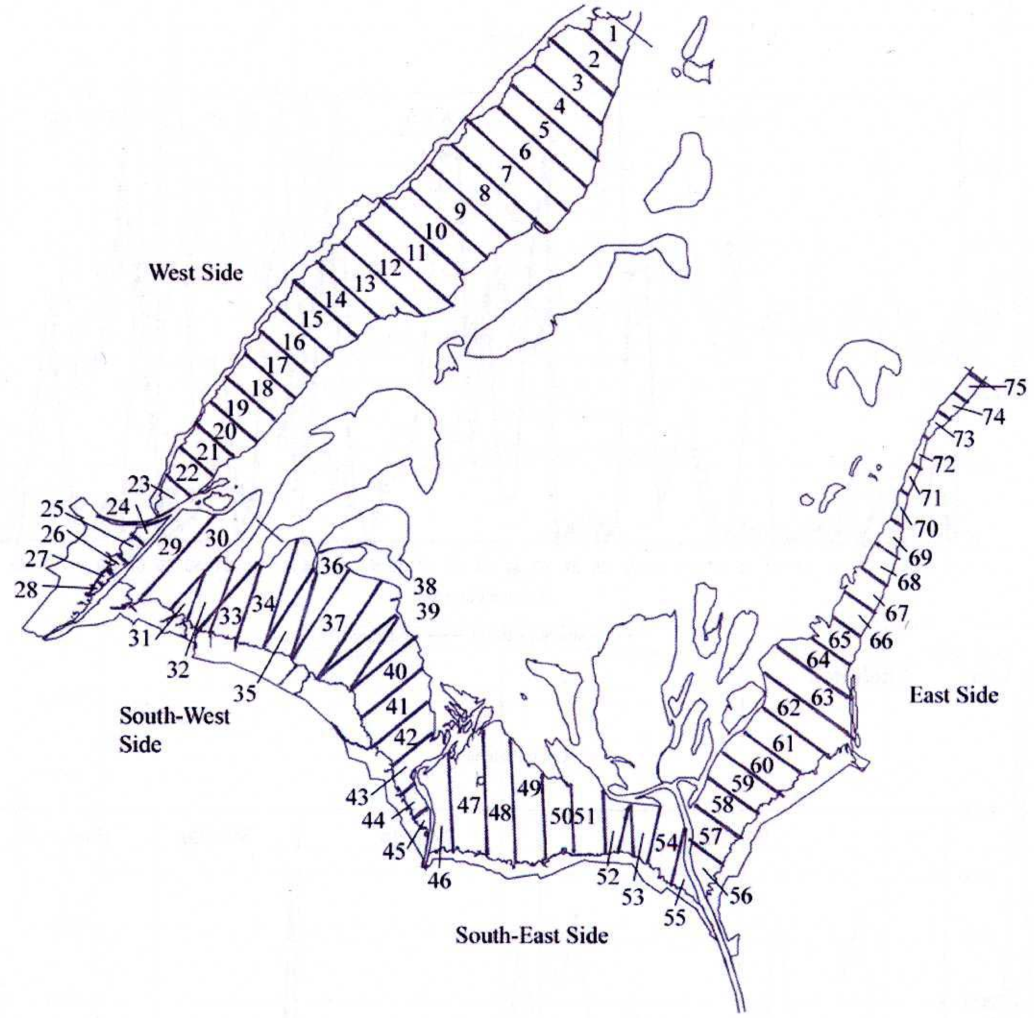


Figure 8.4 Units for summarising the along-shore distribution of birds on the inner banks of The Wash, CEH low tide surveys. Taken from Yates and others (2004).

9 Possibilities for data analysis

The need for a future research programmes addressing aspects of the impacts of suction dredging for cockles in The Wash was outlined in Section 7.3. However, some meaningful analyses are probably already possible, using the major data resources identified in Section 8. In this section we briefly provide some suggestions for these analyses. It is important to emphasise that that the extraction and cross-referencing of the data sets will in itself be a major task. There is sufficient spatial resolution in the data sets on benthic invertebrates and sediments (Section 8.3, Figure 8.3) and shorebirds (Section 8.4, Figure 8.4) to allow them to be related to the fishing areas and cockle stock estimates (Sections 8.1 and 8.2, Figure 8.2). Nevertheless, there will always remain some uncertainty about the exact spatial correspondence between dredging activities and the 'response' variables, so that the interpretation of results of analyses must be somewhat tentative.

9.1 Recommendations for future analyses

Some of the analyses possible with existing data have already been performed. For example, Dare (1999) has calculated food requirements for knot and oystercatcher in The Wash and related these to the availability of cockles, Stillman and others (2003) have used a behaviour based model to examine how foraging oystercatchers interact with their food resources, and Atkinson and others (2003) have analysed population dynamics of knot and oystercatcher in The Wash in relation to trends in shellfish abundance. We will focus on some of the possibilities for new analyses.

- Partitioning of cockle mortality into its identifiable components could provide some insights into how fishing activities affect the year-to-year survival of cockles and the availability of cockles for shellfish-eating birds. Bell and others (2001) performed such an analysis for the Burry Inlet and put forward the idea of a compensation threshold for exploitation (see Section 4.6). The existence and measurement of such a threshold in The Wash would be very important for defining sustainable exploitation levels. The data elements are: (i) cockle stocks and their structure and distribution between beds (ESFJC data for 1992 onwards); (ii) commercial cockle landings and their distribution between beds (ESFJC data); (iii) total numbers of knot and oystercatcher in each month (WeBS data and CEH low-tide surveys); (iv) distribution of birds between beds (CEH low-tide surveys); (v) temperature data, for the modelling of bird food requirements and cockle growth. The analysis would include calculation of quantities and sizes of cockles taken by birds and fisheries. These would be compared with measured changes in cockle abundance to gain an insight into how the overall mortality is accounted for by known sources. It will be important to perform calculations for individual beds before obtaining overall Wash figures. This is partly because of the spatial structuring within this large site, but also because the cockle survey data are unlikely to be comprehensive for non-commercial beds in each year.

- Calculations of fishery impacts on the cockle stocks will require indirect as well as direct fishing mortality to be estimated. This in itself is a major analysis. We recommend that a comprehensive analysis be undertaken of the additional mortality components, based on the damage rates and mortality rates reviewed in Section 3. It will be important to consider the uncertainty involved in these estimates, since we have ranges of possible values for parameters, eg for mortality of undamaged rejects from the riddle (Section 3.1).

- We recommend that cockle survey data be examined in relation to the distribution and intensity of fishing since 1992. Particular attention should be paid to the distribution of spatfall in relation to fishing, and the survival of the stock to recruit to fishable size.

- We also recommend that historical and current cockle survey data be examined in relation to sediment types. Given the potentially greater impact of suction dredging in the areas of finer sediment, it will be important to determine how much of the total Wash cockle stock occurs in these areas in most years. Analyses could make use of the broad sediment classes identified using satellite imagery by Yates and others (1993b) (see Section 8.5).

- Invertebrate community data should be analysed in relation to the intensity of fishing effort. CEH survey data (Section 8.3, Figure 8.3) can be divided among the fishing areas (Figure 8.2). Two hypotheses can be examined: (i) that the structure of the invertebrate communities is related to the intensity of dredging effort; and (ii) that the abundance of individual species (particularly *Macoma balthica*) is related to the intensity of dredging effort. Particular care will be needed to distinguish between differences that are due to simple covariation, ie the fact that the areas of highest commercial cockle density, favoured by the fishermen, may be naturally different in their invertebrate communities from other areas, and differences due to the impact of fishing activity. Supplementary data on sediment composition are likely to be needed in these analyses, in order to explain differences in communities that are not due to fishing. Invertebrate community data for 1986, before the start of suction dredging in The Wash, should provide a baseline for the determination of possible impacts, although some reference will need to be made to other fishing methods (blowing) used at that time. Fishing intensity data would need to be summarised for a variety of time periods (single season, series of seasons) in order to discover the temporal scales at which invertebrate communities respond and recover.

- Similar analyses could be undertaken to explore relationships between sediment characteristics and the intensity of fishing effort, and to determine whether fishing has influenced the distribution of birds within The Wash. Again, care would be needed to distinguish between covariation and response.

These are only some of the analyses that will be possible. It is likely that ongoing management for fishery and nature conservation objectives will identify more focused research questions that could be addressed using the existing data resource.

9.2 Future monitoring

Some of the needs for future research have been set out in Section 7.3. This focuses on the need to understand the components of the dredging process and their implications for benthic communities and environments and the wider ecosystem. Management will also require routine monitoring of fishing effort, cockle stocks, benthos and birds. Monitoring will provide two functions: (i) a data resource for addressing research questions of relevance to management; and (ii) measurement of outcomes against management targets (or limits). It is important, therefore, that any future monitoring programme is designed with reference to the chosen measures of the status of features of nature conservation importance.

To a great extent, the important monitoring schemes are already in place – invertebrates, sediments, cockle stocks and fishing effort, bird distribution. However, it will be important to ensure that all future monitoring is undertaken as an integrated whole. For example, it might be useful to adopt the approach suggested by Durell and others (2005a) for identifying habitat units and designing efficient monitoring programmes for bird food supplies. Given the importance of sediment type in determining the potential for impact by suction dredging, it would also be useful to undertake some basic sediment monitoring alongside the cockle surveys. The frequency of monitoring effort will be dictated by management needs and the resources available. Fishing effort monitoring would need to be ongoing, cockle surveys twice yearly, invertebrate, sediment and low tide bird surveys periodical (5 years?). Whatever the frequency of monitoring, particular care will be needed to ensure that a common set of spatial reference points be used for all surveys. This could be as simple as ensuring that the boundaries and names of individual beds are consistent between different surveys.

10 References

ADKINS, B.E., HARBO, R.M., & BOURNE, N. 1983. An evaluation and management considerations of the use of a hydraulic clam harvester on intertidal clam populations in British Columbia. *Canadian manuscript report of fisheries and aquatic sciences*, No. 1716.

ALLEN, P.L. 1995. *An assessment of the impact of hydraulic cockle dredging on the macroinvertebrate faunas of Traeth Lafan, North Wales.* Contract Report for the Countryside Council of Wales, FC 73-01-86, Bangor.

ANDREWS, J. 1974. Death on the sands. *Birds*, 5, 32-33.

ATKINSON, P.W., and others. 2003. Changes in commercially fished shellfish stocks and shorebird populations in the wash, England. *Biological Conservation*, 114, 127-141.

BAILEY, M., BAMBER, R., & CHIMONIDES, P.D.J. 1999. *Great Ouse estuary. Biological surveys. 16 year data review.* Report to Environment Agency, Ecomaris, Huntingdon.

BELL, M.C., and others. 2001. Fisheries and bird predation as components of cockle (*Cerastoderma edule*) mortality in the Burry Inlet, South Wales. *ICES CM 2001/J:01* (mimeo).

BERGHAHN, R. 1987. The Wadden Sea as a nursery for fish and crustacean species. *Proceedings of the 5th International Wadden Sea Symposium, Esbjerg, 1986*, 69-86.

BEUKEMA, J.J. 1991. The abundance of shore crabs *Carcinus maenas* (L). on a tidal flat in the Wadden Sea after cold and mild winters. *Journal of Experimental Marine Biology and Ecology*, 153, 97-113.

BEUKEMA, J.J. 1992. Dynamics of juvenile shrimp *Crangon crangon* in a tidal-flat nursery of the Wadden Sea after mild and cold winters. *Marine Ecology Progress Series*, 83, 157-165.

BEUKEMA, J.J., and others. 1993. Year-to-year variability in the biomass of macrobenthic animals on tidal flats of the Wadden Sea: how predictable is this food source for birds? *Netherlands Journal of Sea Research*, 31, 319-330.

BOYDEN, C.R. 1971. A comparative study of the reproductive cycles of the cockles *Cerastoderma edule* and *C. glaucum*. *Journal of the Marine Biological Association of the United Kingdom*, 51, 605-622.

BRADSHAW, C., and others. 2000. The effects of scallop dredging on gravelly seabed communities. *In*: M.J. KAISER & S.J. DE GROOT, eds. *Effects of fishing on non-target species and habitats. Biological, conservation and socio-economic issues,* 83-104. London: Blackwell Science.

BUDD, G.C. 2002. Dense *Lanice conchilega* in tide-swept lower shore sand. *Marine Life Information Network: Biology and Sensitivity Key Information Sub-programme* [cited online 1/25/2005]. Plymouth: Marine Biological Association of the United Kingdom. Available from: http://www.marlin.ac.uk/biotopes/bio_basicinfo_LGS.Lan.htm.

COEN, L.D. 1995. *A review of the potential impacts of mechanical harvesting on subtidal and intertidal shellfish resources*. South Carolina Department of Natural Resources, Marine Resources Research Institute.

COFFEN-SMOUT, S.S. 1998. Shell strength in the cockle *Cerastoderma edule* L. under simulated fishing impacts. *Fisheries Research*, 38, 187-191.

COFFEN-SMOUT, S.S., & REES, E.I.S. 1999. Burrowing behaviour and dispersion of cockles *Cerastoderma edule* L. following simulated fishing disturbance. *Fisheries Research*, 40, 65-72.

COLLIE, J.S., and others. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. *Journal of Animal Ecology*, 69, 785-798.

COMMON WADDEN SEA SECRETARIAT. 2002. *Shellfish Fisheries: An overview of policies for shellfish fishing in the Wadden Sea.* Common Wadden Sea Secretariat, Wilhelmshaven.

CONNOR, D.W., and others. 1997. *Marine biotope classification for Britain and Ireland. Volume 1. Littoral biotopes.* Peterborough: MNCR/JNCC Report No. 229, JNCC.

COOK, W. 1991. *Studies on the effects of hydraulic dredging on cockle and other macroinvertebrate populations 1989-1990*. North Western and North Wales Sea Fisheries Committee.

COTTER, A.J.R., and others. 1993. An experiment on the effects of tractor dredging on cockles in the Burry Inlet, South Wales. *ICES Shellfish Committee Doc. CM 1993/K:24* (mimeo).

COTTER, A.J.R., and others. 1997. Trial of a tractor dredger for cockles in Burry Inlet, South Wales. *ICES Journal of Marine Science*, 54, 72-83.

CURRIE, D.R., & PARRY, G.D. 1996. Effects of scallop dredging on a soft-sediment community: a large-scale experimental study. *Marine Ecology Progress Series*, 134, 131-150.

CURRIE, D.R., & PARRY, G.D. 1999. Impacts and efficiency of scallop dredging on different soft substrates. *Canadian Journal of Fisheries and Aquatic Sciences*, 56, 539-550.

DAHL, K., and others. 1994. Status, trends, regulation and ecological effects of the Wadden Sea fishery. *Ophelia*, 6(Suppl.), 87-97.

DARE, P.J. 1999. *Health of the Wash ecosystem: Shorebird population trends, food supplies and possible shellfisheries interactions in the Wash, 1972-1997*. Report to English Nature.

DARE, P.J., and others. 2004. *Historical and current status of cockle and mussel stocks in The Wash.* Lowestoft: CEFAS.

DAVIDSON, P.E. 1967. A study of the oystercatcher (*Haematopus ostralegus* L.) in relation to the fishery for cockles (*Cardium edule* L.) in the Burry Inlet, south Wales. *Fisheries Investigations (London) Series 2*, 25(7), 1-28.

DAVIS, S.E.B., and others. 2004. *Survey of Solway cockle grounds 2004.* Internal Report No. 05/04. Aberdeen: Fisheries Research Services.

DE VLAS, J. 1982. De effecten van de kokkelvisserij op de bodemfauna van Waddenzee en Oosterschelde. *RIN-rapport* 82/19. Texel.

DE VLAS, J. 1987. Effects of cockle fisheries on the macrobenthos in the Wadden Sea. *Proceedings of the 5th International Wadden Sea Symposium, Esbjerg, 1986*, 215-227.

DUGDALE, R., PLATER, A., & ALBAKANIS, K. 1987. The fluvial and marine contribution to the sediment budget of the Wash. *In:* P. Doody, & B. Barnett, eds. The Wash and its environment. Report of a conference held on 8-10 April 1987 at Horncastle, Lincolnshire, 37-47. *Research and Survey in Nature Conservation*, No. 7. Peterborough: Nature Conservancy Council.

DURELL, S.E.A. LE V. DIT, and others. 2005a. A strategy for baseline monitoring of estuary Special Protection Areas. *Biological Conservation*, 121, 289-301.

DURELL, S.E.A. LE V. DIT, and others. 2005b. Modelling the efficacy of proposed mitigation areas for shorebirds: a case study on the Seine estuary, France. *Biological Conservation*, 123, 67-77.

ELLIOTT, M., and others. 1998. *Intertidal Sand and Mudflats & Subtidal Mobile Sandbanks (volume II). An overview of dynamics and sensitivity characteristics for* *conservation management of marine SACs*. Scottish Association for Marine Science (UK Marine SACs Project).

ENS, B.J., & CAYFORD, J.T. 1996. Feeding with other oystercatchers. *In:* J.D. GOSS-CUSTARD, ed. *The oystercatcher: from individuals to populations*, 77-104. Oxford: Oxford University Press.

ENS, B.J., DE JONG, M.L., & TER BRAAK, C.J.F. 2004a. *EVA II deelproject C4: resultaten kokkelvisexperiment Ameland.* Alterra-rapport 945. Wageningen: Alterra.

ENS, B.J., SMAAL, A.C., & DE VLAS, J. 2004b. *The effects of shellfish fishery on the ecosystems of the Dutch Wadden Se and Oosterschelde*. Final report on the second phase of the scientific evaluation of the Dutch shellfish fishery policy (EVA II). Alterra-rapport 1011, RIVO-rapport C056/04, RIKZ-rapport RKZ/2004.031. Wageningen: Alterra.

EVANS, G., & COLLINS, M. 1987. Sediment supply and deposition in the Wash. *In:* P. DOODY, & B. BARNETT, eds. The Wash and its environment. Report of a conference held on 8-10 April 1987 at Horncastle, Lincolnshire, 48-63. *Research and Survey in Nature Conservation*, No. 7. Peterborough: Nature Conservancy Council.

FERNS, P.N., ROSTRON, D.M., & SIMAN, H.Y. 2000. Effects of mechanical cockle harvesting on intertidal communities. *Journal of Applied Ecology*, 37, 464-474.

FOSTER-SMITH, R.L., SOTHERAN, I., & WALTON, R. 1997. *Broadscale mapping of habitats and biota of the sublittoral seabed of the Wash. Final report of the 1996 Broadscale Mapping Project survey*. Report to English Nature and EJSFC.

FOWLER, S.L. 1989. Nature conservation implications of damage to the seabed by commercial fishing operations. *Nature Conservancy Council, Contract Report*, No. 79.

FRANKLIN, A., 1972. *The cockle and its fisheries.* Laboratory Leaflet (New Series) No. 26, MAFF Directorate of Fisheries Research, Burnham-on-Crouch.

FRANKLIN, A., & PICKETT, G.D. 1968. *Cockle resources of the Wash, 1967-68.* Shellfish Information Leaflet No. 11. Burnham-on-Crouch: MAFF Directorate of Fisheries Research.

FRANKLIN, A., & PICKETT, G.D. 1972. Introduction of the hydraulic cockle dredge. *Commercial Fishing*, 3(2), 18-22.

FRANKLIN, A., & PICKETT, G.D. 1973. *Wash ploughing-out experiments 1972-73.* Surveys and reports by Burnham Fisheries Laboratory Staff No. 191. Burnham-on-Crouch: MAFF.

FRANKLIN, A., & PICKETT, G.D. 1978. Studies on the indirect effects of fishing on stocks of cockles, *Cardium edule*, in the Thames Estuary. *Fisheries Research Technical Report*, No. 42. Lowestoft: MAFF Directorate of Fisheries Research.

GOSS-CUSTARD, J.D., ed. 1996. *The oystercatcher: from individuals to populations.* Oxford: Oxford University Press.

GOSS-CUSTARD, J.D., JONES, R.E., & NEWBERRY, P.E. 1977. The ecology of the Wash. I. Distribution and diet of wading birds (Charadrii). *Journal of Applied Ecology*, 14, 681-700.

GOSS-CUSTARD, J.D., and others. 2004. When enough is not enough: shorebirds and shellfishing. *Proceedings of the Royal Society of London B*, 271, 233-237.

HALL, S.J., & HARDING, M.J.C. 1997. Physical disturbance and marine benthic communities: the effects of mechanical harvesting of cockles on non-target benthic infauna. *Journal of Applied Ecology*, 34, 497-517.

HANCOCK, D.A. 1971. The role of predators and parasites in a fishery for the mollusc *Cardium edule* L. *In:* P.J. DEN BOER, & G. R. GRADWELL, eds. *Dynamics of Populations*, 419-439. *Proceedings of the Advanced Study Institute on 'Dynamics of Numbers in Populations'*. Netherlands: Oosterbeek.

HANCOCK, D.A., & URQUHART, A.E. 1965. The determination of natural mortality and its causes in an exploited population of cockles (*Cardium edule* L.). *Fisheries Investigations, London (Series 2)*, 24, 1-40.

HAUTON, C., ATKINSON, R.J.A., & MOORE, P.G. 2003. The impact of hydraulic blade dredging on a benthic megafaunal community in the Clyde Sea area, Scotland. *Journal of Sea Research*, 50, 45-56.

HIDDINK, J.G. 2003. Effects of suction dredging for cockles on non-target fauna in the Wadden Sea. *Journal of Sea Research*, 50, 315-323.

HOPPER, A.G. 1986. *Cockle dredging.* Unpublished Memorandum to members of the White Fish Development Group, IDU 2103, White Fish Authority.

HORWOOD, J.W., & GOSS-CUSTARD, J.D. 1977. Predation by the oystercatcher, *Haematopus ostralegus* (L.) in relation to the cockle *Cerastoderma edule* (L.) fishery in the Burry Inlet, South Wales. *Journal of Applied Ecology*, 14, 139-158.

HUGGETT, D. 1992. *Some aspects of foreshore fishing for shellfish and bait by hand, dredge and suction dredgers*. Sandy: RSPB.

JENNINGS, S., & KAISER, M.J. 1998. The effects of fishing on marine ecosystems. *Advances in Marine Biology*, 34, 202-252.

JESSOP, R.W., LOWRY, M., & GRAVES, K. 2003. *Eastern Sea Fisheries District Research Report 2000.* King's Lynn: Eastern Sea Fisheries Joint Committee.

JOHNSON, K.A. 2002. *A review of national and international literature on the effects of fishing on benthic habitats.* US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Silver Spring. NOAA Technical Memorandum NMFS-F/SPO-57. Available from: http://www.nmfs.noaa.gov/habitat/habitatprotection/essentialfishhabitat10.htm.

JOHNSON, R. 1988. Cockle dredging – improved performance using a solids pump. *Sea Fish Industry Authority, Seafish Report*, No. 348.

JONES, S.R., & JEFFS, T.M. 1991. Near-surfac sea temperatures in coastal waters of the North Sea, English Channel and Irish Sea. *Fisheries Research Data Report*, No. 24. Lowestoft: MAFF Directorate of Fisheries Research.

KAISER, M.J., BROAD, G., & HALL, S.J. 2001. Disturbance of intertidal soft-sediment benthic communities by cockle hand raking. *Journal of Sea Research*, 45, 119-130.

KAISER, M.J., EDWARDS, D.B., & SPENCER, B.E. 1996. Infaunal community changes as a result of commercial clam cultivation and harvesting. *Aquatic Living Resources*, 9, 57-63.

KAMERMANS, P., and others. 2003. *EVA II deeproject H4: Invloed van natuurlijke factoren en kokkelvisserij op de dynamiek van bestanden aan kokkels (*Cerastoderma edule*) en nonnen (*Macoma balthica*) in de Waddenzee, Ooster- en Westerschelde.* RIVO-rapport C058/03, RIVO, Yerseke.

KAUWLING, T.J., & BAKUS, G.J. 1979. *Effects of hydraulic clam harvesting in the Bering Sea.* Report to the North Pacific Fishery Management Council, Tetra Tech Report TC 3224, Pasadena.

KRAAN, C., and others. 2004. *Korte termijn effecten van de mechanische kokkelvisserij in de westelijke Waddenzee op bodemfauna.* Koninklijk NIOZ-Intern Rapport, NIOZ, Texel.

KRISTENSEN, P.S., 1997. Oyster and mussel fisheries in Denmark. *In:* C.L. MACKENZIE, V.G. BURRELl, A. ROSENFIELD, & W.L. HOBART, eds. *The history, present condition, and future of the molluscan fisheries of North and Central America and Europe. Volume 3, Europe*, 25-38. NOAA Technical Report NMFS 129, US Department of Commerce.

LAWLER, A.R., BELL, M.C., & ADDISON, J.T., in prep. *Fluctuations in brown shrimp (*Crangon crangon*) abundance in The Wash – climate, biological or anthropogenic factors?*

LEOPOLD, M.F., and others. 2003a. *EVA II deelproject C1/3: de effecten van mechanische kokkelvisserij op de benthische macrofauna en hun habitat.* Alterra-rapport 955. Wageningen: Alterra.

LEOPOLD, M.F., and others. 2003b. EVA II deelproject C2: langjarige trends in aantallen wadvogels, in relatie tot de kokkelvisserij en het gevoerde beleid in deze. Alterra-rapport 954. Wageningen: Alterra.

MANDER, M.R., & TRUNDLE, C.J. 2000. *Eastern Sea Fisheries District Research Report 2000.* King's Lynn: Eastern Sea Fisheries Joint Committee.

MANDER, M.R., & TRUNDLE, C.J. 2001. *Eastern Sea Fisheries District Research Report 2001.* King's Lynn: Eastern Sea Fisheries Joint Committee.

MANDER, M.R., TURNER, J.C., & HOWARD, S.P., 1999. *Eastern Sea Fisheries District Research Report 1999.* Eastern Sea Fisheries Joint Committee, King's Lynn.

MOORE, J. 1991. *Studies on the impact of hydraulic cockle dredging on intertidal sediment flat communities*. Report to the Nature Conservancy Council, Field Studies Council Research Centre, Pembroke, Report FSA/RC/4/91.

PERKINS, E.J. 1988. *The impact of suction dredging upon the population of cockles in Auchencairn Bay, 1988.* Report to the Nature Conservancy Council, South-west Region, Scotland, NC 232 I, Solmaris.

PICKETT, G. 1973. *The impact of mechanical harvesting on the Thames Estuary cockle fishery.* Laboratory Leaflet (New Series) No. 29. Lowestoft: MAFF Directorate of Fisheries Research.

PIERSMA, T., & KOOLHAAS, A. 1997. *Shorebirds, shellfish(eries) and sediments around Griend, western Wadden Sea, 1988-1996*. NIOZ-rapport 1997-7, NIOZ, Texel.

PIERSMA, T., and others. 2001. Long-term indirect effects of mechanical cockle-dredging on intertidal bivalve stocks in the Wadden Sea. *Journal of Applied Ecology*, 38, 976-990.

PIHL, L., & ROSENBERG, R. 1984. Food selection and consumption of the shrimp *Crangon crangon* in some shallow marine areas in western Sweden. *Marine Ecology Progress Series*, 15, 159-168.

POLLITT, M.S., and others. 2003. *The Wetland Bird Survey 2000-01: Wildfowl and Wader Counts*. BTO / WWT / RSPB / JNCC, Slimbridge.

PRATER, A.J. 1981. *Estuary Birds of Britain and Ireland.* Calton: T. & A. D. Poyser.

REES, E.I.S. 1996. *Environmental effects of mechanised cockle fisheries: a review of research data.* Report to MAFF Marine Environmental Protection Division, University of Wales, Bangor.

REISE, K. 1982. Long-term changes in the macrobenthic invertebrate fauna of the Wadden Sea: are polychaetes about to take over? *Netherlands Journal of Sea Research*, 16, 29-36.

RICHARDSON, C.A., IBARROLA, I., & INGHAM, R.J. 1993. Emergence pattern and spatial distribution of the common cockle *Cerastoderma edule*. *Marine Ecology Progress Series*, 99, 71-81.

RIEMANN, B., & HOFFMANN, E. 1991. Biological consequences of dredging and bottom trawling in the Limfjord, Denmark. M*arine Ecology Progress Series*, 69, 171-178.

SANCHEZ-SALAZAR, M.E., GRIFFITHS, C.L., & SEED, R. 1987. The effect of size and temperature on the predation of cockles *Cerastoderma edule* (L.) by the shore crab *Carcinus maenas* (L.). *Journal of Experimental Marine Biology and Ecology*, 111, 181-193.

SEAMAN, M.N.L., & RUTH, M. 1997. The molluscan fisheries of Germany. *In*: C.L. MACKENZIE, V.G. BURRELL, A. ROSENFIELD, & W.L. HOBART, eds. *The history,* *present condition, and future of the molluscan fisheries of North and Central America and Europe. Volume 3, Europe*, 57-84. NOAA Technical Report NMFS 129, US Department of Commerce.

SIDDLE, W. 1988. Updated handbook on the W.F.A. cockle dredge of 1968. *Sea Fish Industry Authority, Technical Report*, No. 333.

SMITH, E.P., ORVOS, D.R., & CAIRNS, J. 1993. Impact assessment using the before-after-control-impact (BACI) model: concerns and comments. *Canadian Journal of Fisheries and Aquatic Sciences*, 50, 627-637.

STILLMAN, R.A., and others. 2003. An individual behaviour-based model can predict shorebird mortality using routinely collected shellfishery data. *Journal of Applied Ecology*, 40, 1090-1101.

THRUSH, S.F., and others. 1996. Scale-dependent recolonization: the role of sediment stability in a dynamic sandflat habitat. *Ecology*, 77, 2472-2487.

TRUNDLE, C.J., & JESSOP, R.W. 2002. *Eastern Sea Fisheries District Research Report 2002.* King's Lynn: Eastern Sea Fisheries Joint Committee.

TUCK, I.D., and others. 2000. The impact of water jet dredging for razor clams, *Ensis* spp., in a shallow sandy subtidal environment. *Journal of Sea Research*, 43, 65-81.

TYLER-WALTERS, H. 2003. *Cerastoderma edule*. Common cockle. *Marine Life Information Network: Biology and Sensitivity Key Information Sub-programme* [cited online 29/11/2004]. Marine Biological Association of the United Kingdom, Plymouth. Available from: http://www.marlin.ac.uk/species/Cerastodermaedule.htm.

WFA 1967. Continuous delivery dredge for cockles. White Fish Authority. *R & D Bulletin* No. 25.

WFA. 1968. Hydraulic continuous lift dredge for harvesting cockles. *White Fish Authority, Technical memorandum*, No. 44.

WIGGINS, J. 1991. *Survival of cockles rejected by cockle dredgers.* Kent & Essex Sea Fisheries Committee, unpublished report.

WOODIN, S.A., LINDSAY, S.M., & WETHEY, D.S. 1995. Process-specific recruitment cues in marine sedimentary environments. *Biological Bulletin*, 189, 49-58.

WOODIN, S.A., MARINELLI, R.L. & LINDSAY, S.M. 1998. Process-specific cues for recruitment in sedimentary environments: Geochemical signals? *Journal of Marine Research*, 56, 535-558.

YATES, M.G., and others. 2002. Littoral sediments of the Wash and North Norfolk Coast SAC: The 1998 and 1999 surveys of intertidal sediment and invertebrates. *English Nature Research Reports*, No. 470.

YATES, M.G., and others. 2004. Low tide surveys of The Wash Special Protection Area. Final report of the winter 2002-2003 shorebird survey. *English Nature Research Reports*, No. 589.

YATES, M.G., and others. 1993a. Sediment characteristics, invertebrate densities and shorebird densities on the inner banks of the Wash. *Journal of Applied Ecology*, 30, 599-614.

YATES, M.G., and others. 1993b. The use of satellite imagery to determine the distribution of intertidal surface sediments of The Wash, England. *Estuarine, Coastal and Shelf Science*, 36, 333-344.

YOUNG, E.F., BIGG, G.R., & GRANT, A. 1996. A statistical study of environmental influences on bivalve recruitment in the Wash, England. *Marine Ecology Progress Series*, 143, 121-129.

YOUNG, E.F., and others. 1998. A modelling study of environmental influences on bivalve settlement in the Wash, England. *Marine Ecology Progress Series*, 172, 197-214.

ZWARTS, L., & BLOMERT, A.-M., 1992. Why Knot *Calidris canutus* take medium-sized *Macoma balthica* when six prey species are available. *Marine Ecology Progress Series*, 83, 113-128.

Appendix 1 Calculation of components of mortality for cockles rejected at the riddle

These calculations are based on measuring mortality in three samples of cockles, as in the aquarium and cage experiments of Mander & Trundle (2001): (i) a control sample of hand picked cockles, in which mortality is assumed to be due to natural factors (ie not fishing) and experimental culture conditions (cage or aquarium) only; (ii) a sample of rejects from the riddle of a suction dredger, in which there is no obvious external damage; and (iii) a sample of riddle rejects with obvious external damage. Mortality in each sample can be resolved into additive, instantaneous components:

Control $$C = -\ln\left(1 - \frac{\%\text{ mortality in control sample}}{100}\right);$$

Undamaged $$U = -\ln\left(1 - \frac{\%\text{ mortality in undamaged sample}}{100}\right) - C;$$

Damaged $$D = -\ln\left(1 - \frac{\%\text{ mortality in damaged sample}}{100}\right) - C - U.$$

This then allows mortality due to each component to be calculated on a percentage scale. The mortality due to the fishing process only, corrected for mortality in the control sample, is calculated as

$$\text{fishing mortality }(\%) = 100 \times \left(1 - e^{-U}\right);$$

and the mortality due to damage, corrected for mortality due to the fishing process and for mortality in the control sample, is calculated as

$$\text{damage mortality }(\%) = 100 \times \left(1 - e^{-D}\right).$$

Note that this is the mortality due to damage **only**, ie it is the additional mortality caused just by damage to the discarded cockles. The mortality due to both the fishing and damage, ie the additional fishing mortality among the damaged component of the discards, is calculated as

$$\text{fishing} + \text{damage mortality }(\%) = 100 \times \left(1 - e^{-(U+D)}\right).$$

ENGLISH NATURE

Research Information Note

English Nature Research Reports, No. 670

Cockle Suction Dredging in The Wash and North Norfolk Coast European marine site: Desk study to assess impacts

Note written by English Nature Project Officer: Conor Donnelly
Report Authors: Michael C. Bell and Peter Walker Date: October 2005
Keywords: Cockles, suction dredging, undersize, sheltered sediments, oystercatcher , knot Report

Introduction

- The Wash has supported an important fishery for cockles *Cerastoderma edule* for more than a century. It has international and national wildlife importance as an SAC, SPA, Ramsar Site and SSSI reflecting the importance of the extensive intertidal and subtidal habitats of The Wash and their importance for shorebirds.

- Suction dredging has been the main method of fishing for cockles in The Wash since the late 1980s. A review of the Dutch shellfishery policy in the Wadden Sea concluded cockle suction dredging damaged the sediment, benthos and contributed to declines in shorebirds. The Dutch government ruled suction dredging in the Wadden Sea was incompatible with ecologically sustainable economic development and the fishery closed in 2005. Danish and German cockle fisheries in the Wadden Sea were already closed in 1991 on the basis of negative ecological effects caused by the fishery. Despite this it doesn't automatically follow that suction dredging for cockles in The Wash is incompatible with the nature conservation features of the sites.

What was done

- The report reviews available evidence on impacts of cockle suction dredging on cockles, their habitat and associated wildlife. Comparison is made with impacts of other cockle fishing techniques. The report describes the relevance of these studies to The Wash, identifies gaps in knowledge requiring research, and considers ways to mitigate any impacts of suction dredging by managing and modifying fishing activities. The available data on cockle fisheries, stocks and the environment and biota of The Wash which may allow further analysis of possible impacts is reviewed.

Results and conclusions

- Suction dredging for cockles has the potential to affect the cockles themselves, non-target benthic invertebrates, predators of cockles and the sediment.

- In cockles, the main effect is damage and mortality of undersized cockles rejected at the dredge head and deck riddle. It seems likely an average of about 27% additional fishing mortality in dredged areas can be inflicted on undersized cockles beyond the direct fishing mortality of the retained catch. Spatial management and technical measures (*e.g.* limits on discard rates) are likely to be effective in mitigating this.

- In areas of mobile sediment, suction dredging doesn't appear to have strong adverse effects on cockle spatfall success. Invertebrate communities in these exposed situations are, like their habitat, dynamic and dredge impacts are undetectable within days to weeks. Some concern remains about effects on structural components of such communities (*e.g.* polychaete tubes) and about effects on the bivalve *Macoma balthica*, an alternative food resource for cockle-eating birds particularly knot.

- In sheltered muddy areas, suction dredging can cause loss of fine silts. Cockles are important in promoting sediment stability and in adding fine particles to sediment through biodeposition. Loss of these functions may exacerbate loss of silts and cause prolonged recovery times. Invertebrate communities in muddy, sheltered areas are also much more vulnerable to disturbance by suction dredging than communities in more exposed areas. Eelgrass beds are particularly vulnerable.

- There is a lack of studies of suction dredging effects on environment and communities of The Wash. The Wash appears to be at the sandy, exposed end of the spectrum of sites where suction dredging occurs and for this reason, sediments and benthic communities over much of The Wash are thought to be relatively resilient to the effects of suction dredging. However, there are also sheltered, muddier, areas where suction dredging occurs. Greater impacts and longer recovery times would be expected in these areas. This may also apply to *Lanice* biotopes in sandy areas.

- Cockle fishing has been shown to affect knot and oystercatcher populations by direct competition for resources and by modifying their habitat. Oystercatcher populations in The Wash have been adversely affected by low cockle abundance in years when mussel stocks were also low. Suction dredging may have contributed to this effect by out-competing oystercatchers for larger cockles but the importance of this effect in comparison with natural variations in cockle abundance is not known. Effects of dredging on non-target benthic invertebrates are thought not to have affected bird populations in The Wash. There are some grounds for concern that dredging may affect populations of *Macoma balthica*. This could potentially impact knot but there is no evidence this has actually occurred possibly because the main concentrations of *Macoma* in The Wash are thought to be further upshore than the cockle fishing areas.

English Nature's viewpoint

- English Nature notes the potential for adverse impacts of cockle suction dredging on sheltered sediments and that these vulnerable areas occur in The Wash. We note the potential for impacts on undersized cockle, *Macoma* and structural components of sandy habitats, notably *Lanice* biotopes. These impacts may be addressed through spatial management and technical measures which we hope to discuss further with fisheries managers and industry. There are still significant uncertainties over impacts of this technique in The Wash which need to be addressed by research.

Selected references

ATKINSON, and others. 2003. Changes in commercially fished shellfish stocks and shorebird populations in the wash, England. *Biological Conservation*, 114, 127-141.

DARE, and others. 2004. *Historical and current status of cockle and mussel stocks in The Wash*. Lowestoft: CEFAS.

Further information

English Nature Research Reports and their *Research Information Notes* are available to download from our website: www.english-nature.org.uk

For a printed copy of the full report, or for information on other publications on this subject, please contact the Enquiry Service on 01733 455100/101/102 or e-mail enquiries@english-nature.org.uk

ENGLISH NATURE

English Nature is the Government agency that champions the conservation of wildlife and geology throughout England.

This is one of a range of publications published by:
External Relations Team
English Nature
Northminster House
Peterborough PE1 1UA

www.english-nature.org.uk

Cover printed on Character Express, post consumer waste paper, ECF.

ISSN 0967-876X

Cover designed and printed by Status Design & Advertising, 2M, 5M, 5M.

Front cover photographs:
Top left: Using a home-made moth trap.
Peter Wakely/English Nature 17,396
Middle left: Co_2 experiment at Roudsea Wood and Mosses NNR, Lancashire.
Peter Wakely/English Nature 21,792
Bottom left: Radio tracking a hare on Pawlett Hams, Somerset.
Paul Glendell/English Nature 23,020
Main: Identifying moths caught in a moth trap at Ham Wall NNR, Somerset.
Paul Glendell/English Nature 24,888