ONE OF THE MANY FACTORS threatening the ecological integrity of the Wadden Sea, a coastal shallow water ecosystem in the northern part of the Netherlands, is bottom disturbance due to fishing, particularly mechanical dredging for shellfish. Because of its far-reaching national and international ecological impacts, fishing has been a major policy issue for several decades.

Tidal flats occur along the edges of shallow seas with soft-sediment bottoms, in areas where the tidal range is at least a meter or so (Eisma 1998; van de Kam et al. 2004). The lowest intertidal areas are largely barren, except for seagrass meadows (Zostera) and reefs formed by shellfish such as oysters (Ostrea) or tube worms (e.g., Sabellaria). Intertidal areas are inundated at least once per day; higher up are salt marshes, which are more rarely and irregularly inundated. In tropical regions, and even some benign temperate areas such as northern New Zealand, the upper parts of intertidal areas may be covered by mangrove forests rather than salt marsh. Mangroves also have a tendency to cover the regularly inundated parts of intertidal soft sediments, thus reducing the extent of mudflats in many tropical areas. No intertidal deposits occur at high latitudes, farther north than 70° to 73°, as coastlines are either ice covered for most of the year or disturbed by moving ice too frequently for soft-sediment deposits to build up.

Soft-sediment systems worldwide provide living space for a group of highly specialized migrant shorebirds, relatively long-legged small to medium-size birds that breed spread out over boreal to arctic areas in the Northern Hemisphere during June and July and migrate considerable distances to much smaller coastal intertidal ecosystems the world over. From August to May, the birds are found in large concentrations in the Wadden Sea. Long-distance migrant shorebirds are particularly susceptible to the effects of human encroachment on coastal habitats, overexploitation of marine resources, and global climate change (Piersma and Baker 2000;
Piersma and Lindström (2004). A recent survey by the International Wader Study Group showed that of 207 shorebird populations with known population trajectories (out of a total of 511 known shorebird populations), almost half (48%) are in decline, whereas only 16% are increasing (International Wader Study Group 2003). With three times as many populations decreasing as increasing, shorebirds belong to the most globally endangered segment of migrant birds of the world.

This chapter focuses on the role of intertidal ecosystems such as the Wadden Sea in supporting intricate networks of intercontinental shorebird flyways, phenomena for which the Dutch government has pledged responsibility through international agreements such as the Ramsar Convention on Wetlands and the European Union’s Habitats and Birds Directives. Nevertheless, the Dutch government has also allowed mechanical dredging for shellfish. The main objective of this chapter is to show that permitting this activity undermines the government’s commitment to the international agreements.

Signed in 1971 in Ramsar, Iran, the Ramsar Convention on Wetlands (www.ramsar.org) is an intergovernmental treaty that provides the framework for national action and international cooperation on the conservation and wise use of wetlands and their resources. Presently, the convention has 153 contracting parties, with 1,631 designated wetland sites covering a total of 145.6 million hectares on the Ramsar List of Wetlands of International Importance. The Habitats Directive of the European Union (EU) is much more recent, dating from 1992, and aims to ensure biodiversity through the conservation of natural habitats and wild fauna and flora in the continent. Under this directive, EU member states have agreed to design, maintain, or restore natural habitats and species of wild fauna and flora, including the establishment of a coherent European ecological network of special protection areas (SPAs). This network, known as Natura 2000, should enable the natural habitats of the species concerned to be maintained or, where appropriate, restored to a favorable conservation status. The Birds Directive of 1994 embodies a far-reaching protection scheme for all of the continent’s wild birds, particularly those that are threatened and in need of special conservation measures. Under this directive, member states are required to establish SPAs not only for the 194 species designated as threatened, but for all migratory bird species. SPAs, such as wetlands, are scientifically identified areas critical for the survival of the targeted species and form part of Natura 2000. The designation of an area, such as the intertidal flats in the Netherlands’ Wadden Sea, as an SPA gives it a high level of protection from potentially damaging developments.

Of the many factors threatening the ecological integrity of coastal shallow water ecosystems, sustained bottom disturbance from fishing appears to be the most overlooked yet pervasive (Coleman and Williams 2002; Jackson et al. 2001; Worm et al. 2006). Building on the lines of argument developed in Bakker and Piersma (2005) and Piersma (2006), this chapter will outline in some detail how mechanical dredging for shellfish in the Dutch Wadden Sea has led to long-term ecological damage and the loss of shorebird populations dependent on shellfish resources. We begin by describing the geophysical and ecological nature of soft-sediment habitats, especially those in the coastal zone. Then we examine the nature of human disturbances and human-related threats to the integrity of soft-sediment ecosystems in order to
develop the argument in detail for a well-researched case study of a protected inter-
tidal area in the Netherlands where dredging for shellfish led to a cascade of eco-
logical consequences and the disappearance of a significant part of a fully protected
wintering shorebird population. The chapter concludes with a more general dis-
cussion of the incompatibility of bottom-disturbing harvesting practices and the
proper protection of seabed systems.

SOFT-SEDIMENT ECOSYSTEMS

Soft-sediment shores in general, and intertidal sand- and mudflats in particular, in
contrast to rocky shorelines, are in dynamic flux. The nature of the sediments is
determined by the sediment types available, currents, tides, and wind-generated
waves, as well as the presence or absence of ecosystem-engineering organisms (such
as reef-building oysters or mussels, but also subsurface-dwelling species producing
fecal pellets that help consolidate sediments; e.g., Risk and Moffatt 1977; Roth-
schild et al. 1994) and human activities such as bottom-fishing and dredging. Good
general introductions to the nature of intertidal soft-sediment habitats can be found

Coarse-grained sediments mostly occur on wave-exposed shores but may even
be found in sheltered places if currents are strong enough. Fine-grained sediments
accumulate in areas that have some shelter, with lower currents and less wave
action. Biofilms of microscopic algae and bacteria, which produce polymeric sub-
stances, trap and bind sediments, producing a surface that is more resistant to ero-
sive forces (Austen et al. 1999; Paterson 1997). The presence of seagrass meadows
not only suppresses erosion, but also increases the accretion rate relative to unveg-
etated areas (Fonseca and Fisher 1986; Gleason et al. 1979; Ward et al. 1984).

Mussel and oyster beds have similar roles in providing shelter and enhancing
accretion rates by their capacity to increase particle size of flocculate matter (Ver-
weij 1952), but they are prone to erosion by the forces of wind and currents. For
the Wadden Sea, Nehls and Thiel (1993) concluded that the longest-living mussel
beds occurred in areas where they had some degree of protection from storms. In
general, wind and tidal stress factors seem to influence benthic community struc-
tures quite strongly (e.g., Emerson 1989; Thistle 1981; Warwick and Uncles 1980).
Thus one of the most interesting phenomena affecting the appearance and biodi-
versity of intertidal flats is the mutual interaction between abiotic factors (wind
and currents) and the organisms present (Bruno and Bertness 2001; Verweij 1952).
The establishment on bare intertidal flats of species that influence the complexity
of the habitat, such as seagrasses, oysters, mussels, or tubeworms, typically generates
even greater habitat complexity, more variations in sediment structure, and
increased biodiversity.

Intertidal soft-sediment systems are among the most productive natural ecosys-
tems, even those in terrestrial habitats on earth (e.g., Beukema 1975; van de Kam
et al. 2004). To a large extent, this is because the waters and sediments are nutrient
rich and because sunlight has easy access, both in the shallow water layer and on
the mud surface at low tide, enabling high primary productivity, which is then
channeled to the higher trophic layers according to the principle of the food pyramid. Food chains are rather like pyramids, with less numerous predators at the top and a great abundance of sunlight-ccatching plants at the bottom. For instance, one shark will eat many big fish, each of which eats a lot of little fish. These little fish might eat crustaceans that feed on zooplankton, which in turn graze on algae, unicellular plants. In this example, the food chain has six links, but in reality, most have fewer. In every food chain, 10% of the organic matter produced at one link is eaten by the next level. The production of 1 kilogram (kg) of shark meat requires 10 kg of big fish, which requires 100 kg of little fish. Working back through the chain, it therefore requires 100,000 kg of algae for a shark to gain 1 kg in mass (a good summary is presented in Pauly and MacLean 2003).

Food chains in European tidal flat systems such as the Wadden Sea usually consist of four levels, with the fourth level composed of seals and fishermen. Birds and fish form the third level and eat invertebrates such as shellfish, worms, and crustaceans (the second level), which feed on algae (the first level). Thus one could say that invertebrates transfer the nutrients and energy from algae into bite-size food portions for the birds (van de Kam et al. 2004).

HUMAN-INDUCED THREATS TO INTERTIDAL ECOSYSTEMS

Although rich in principle, coastal marine ecosystems have suffered very badly at the hand of humans over the last few hundred years (Jackson et al. 2001; Pauly and MacLean 2003; Worm et al. 2006). Upon discovering the Americas for the Spanish king, Christopher Columbus found it hard going in the Caribbean because the passage of his ships was obstructed by the presence of sea turtles, grazers of seagrass meadows that have since been decimated by humans greedy for their meat and eggs. In most parts of the world, certainly in Europe, intertidal flats have experienced human exploitation from the mid-Holocene onward. Most of the human exploitation of intertidal flats was relatively unintrusive for a long time, as it consisted of small-scale fishing and the taking of shellfish by hand. With the advent of motorized power in the last century, however, as well as the use of large nets and dredges, human exploitation of intertidal flats has come to influence the natural processes a great deal. For example, mussels have been farmed in the western Dutch Wadden Sea since specialists from the province of Zeeland moved in during the early 1960s. This industry not only involves the filling up and dredging out of artificial subtidal mussel beds, but also entails the bringing together of mussel spat from much larger areas, including the nearby intertidal zone as well as outside the Netherlands (Kamermans and Smaal 2002). These mussels may be replaced several times during their lives before final transport to the market, and each replacement involves bottom dredging.

In response to the development of markets for bait used in sport-fishing (angling), techniques to mechanically dredge for lugworms (*Arenicola marina*) were developed in the Netherlands in the early 1980s. Given the considerable depth at which they live (30 to 40 centimeters), dredging for lugworms is very invasive, leaving 40-centimeter-deep gullies, with considerable consequences for the inter-
tial biota (Beukema 1995). In a four-year dredging period, lugworm densities over
a square kilometer declined by half. Simultaneously, total biomass of benthic organ-
isms declined even more with an almost complete local disappearance of the large
sand gaper (Mya arenaria), a bivalve that initially constituted half of the biomass.
Recovery took several years.

Edible cockles (Cerastoderma edule) have not been a popular food in the Nether-
lands, but the demands of foreign markets nevertheless made this fishery profitable,
albeit on a limited scale, from the early 1900s onward. With the discovery of new
markets, notably in countries in the Mediterranean region, and the development
of mechanical harvesting techniques, this fishery has seen a large expansion over
the past decades. Starting in the late 1970s, the dredging for cockles became a ver-
table industry. Ecological studies have shown long-term, near decadal, effects on
rates of recruitment of cockles and another bivalve called the Baltic tellin (Macoma
balthica) (Piersma et al. 2001). Also, in the shorter term, mechanical cockle-dredg-
ing practices appear to be having strong negative ecological impacts (see below).

In the Wadden Sea, reclamation, pollution of various kinds (organochlorines and
heavy metals in the 1960s, fertilizers such nitrates and phosphates in the 1970s, and
many rare and exotic organic compounds since), as well as the release and subse-
quent invasion of exotic species can be counted as threats (van de Kam et al. 2004).
As emphasized by Jackson et al. (2001) in their review, however, among the many
threats to coastal ecosystems, fishing has always been the most significant human dis-
turbance. Especially in modern times, when fishing involves the use of capital- and
energy-intensive mechanical harvesting devices rather than manual or wind power,
this activity plays a primary role in the deterioration of coastal ecosystems. This is
particularly so in the Wadden Sea, where industrial forms of fishing that include bot-
tom nets, scrapes, and dredges induce serious habitat transformation (Bakker and
Piersma 2005). When intertidal structures change as a result, local biodiversity and
its generative processes are greatly reduced. The scenario outlined by Jackson et al.
(2001) certainly applies to the intertidal flats in the Dutch Wadden Sea.

Summarizing detailed faunistic information from the Wadden Sea dating back
to 1869, Reise (1982) concluded that whereas bivalves and some other groups of
invertebrate animals show long-term decreases in species diversity, the smaller poly-
chaete species with short life spans (e.g., Scoloplos armiger) are doing well, as they
can take rapid advantage of environmental disturbances that lead to depletions of
other fauna. Reise attributed the disappearance of 28 common macroinvertebrate
species to the loss of the many microhabitats provided by complex physical struc-
tures such as oyster beds, tubeworm reefs, and seagrass meadows. When mussel beds
and seagrass meadows that have provided shelter, nutrition, and other benefits to
various species disappear, so does the fauna associated with them.

In summary, the evidence that trawling, digging, and dredging have serious neg-
ative effects on the sediment characteristics and community structure of intertidal
flats and other sea bottoms is now overwhelming and paramount (e.g., Collie et al.
2000; Dayton et al. 1995; Hall and Harding 1997; Hall et al. 1990; Jackson et al.
2001; Kaiser et al. 2000; Roberts 1997; Watling and Norse 1998; comprehensive
review in Dieter et al. 2003). Hall (1994, 194), in an early review of physical distur-
bance and marine benthic communities, summarized this by saying: “There is
increasing recognition of the role man plays in physically disturbing marine sediment environments, the most obvious and widespread being commercial fishing."

**Effects of Dredging on Shorebirds in a Protected Ecosystem**

The intertidal flats of the Dutch Wadden Sea are a state nature monument and are protected under the Ramsar Convention and EU’s Habitats and Birds Directives (Reneerkens et al. 2005). Despite the high-level conservation status and widespread scientific concerns about the damaging effects of shellfish dredging on marine benthic ecosystems, three-quarters of these intertidal flats were open to mechanical dredging for edible cockles until 2004. A direct, immediate effect of dredging is the complete removal of all organisms larger than 19 millimeters in the 5-centimeter top layer. As the dredged sites are usually the most biodiverse (Kraan et al. 2007), the activity may also affect smaller cockles; other bivalves such as blue mussels (*Mytilus edulis*), Baltic tellins, and sand gapers; polychaetes; and crustaceans such as shore crabs (*Carcinus maenas*). More indirectly, and over longer time frames, sediments lose fine silts from dredging, which leads to long-term reductions in settlement success in both cockles and Baltic tellins (Hiddink 2003; Piersma et al. 2001).

Between 1997–1998 and 2002–2003, the numbers of wintering red knots (*Calidris canutus*) in Northwest Europe declined by about 25%, from approximately 330,000 to 250,000 (unpublished data of the British Trust for Ornithology [BTO], Dutch Centre for Field Ornithology [SOVON], and others), and in the Wadden Sea by some 80%, from about 100,000 to 20,000 or fewer (van Roomen et al. 2005).

Before we examine whether these declines in red knot numbers can be attributed to the mechanical downfishing of the intertidal food webs in the Wadden Sea, a few words about this shellfish-eating shorebird are necessary.

Red knots are highly specialized with respect to feeding and habitat use. Outside the breeding season in the High Arctic, their occurrence is restricted to open coastal intertidal wetland habitats and their diet to hard-shelled mollusks and crustaceans (fig. 3.1). These birds are sandpipers that breed on High Arctic tundra only, but move south from their disjunct, circumpolar breeding areas to nonbreeding sites on the coasts of all continents (except Antarctica) between latitudes 58° north and 53° south. Because of their specialized sensory capabilities (Piersma et al. 1998), red knots generally eat hard-shelled prey found on intertidal, mostly soft, substrates (Piersma et al. 1995, 2005). As a consequence, ecologically suitable coastal sites are few and far between, so the birds must routinely undertake flights of many thousands of kilometers. Each of the six separate tundra breeding areas hosts a population with a sufficiently distinct appearance in body size and plumage during the breeding season to have been assigned a subspecies names (Piersma and Davidson 1992; Tomkovich 2001). Red knots shared a common ancestor as recently as within the last 20,000 years or so (Buehler and Baker 2005; Buehler et al. 2007), and as a result, the subspecies show little genetic divergence.

In an area of roughly 250 square kilometers in the western Dutch Wadden Sea, we annually sampled knot foods and studied the densities and quality in great detail (e.g., Piersma et al. 2001; van Gils et al. 2006b). Each year from early September into December, immediately after completion of our sampling program, mechan-
ical dredging took place at some of the intertidal flats previously mapped for benthos. Using the black-box GPS data on dredging activity that fishery organizations must present annually to the Dutch government (Kamermans and Smaal 2002), we could categorize one-square-kilometer sample blocks as dredged or undredged (this was partially verified based on observations of damaged sediment surfaces; see Kraan et al. 2007). During the years of our study, red knots consumed mostly first-year cockles (58%, based on 174 samples of between 50 and 100 droppings), and for this reason, we focused our analysis on the effects of dredging on freshly settled first-year cockles, known at this stage as spat (see van Gils et al. 2006a).

In dredged areas, densities of cockle spat remained stable, whereas in undredged areas, they increased by a marginal amount (2.6%) per year (van Gils et al. 2006a). This result is consistent with a previous assessment that showed that dredged areas become unattractive for cockles to settle in, perhaps because such sediments have lost silt and good structure (Piersma et al. 2001). In addition, the quality of cockle spat, indicated by the ratio between the mass of the flesh inside the shell and that of the shell itself, declined by 11.3% per year in dredged areas but remained stable in undredged areas, something we explain by the fact that coarser sediments may lead to worse feeding conditions (Drent et al. 2004) and therefore to reduced body condition in deposit-feeding bivalves such as freshly settled cockles (Rossi et al. 2004). Thus both the abundance and quality of the food of red knots decreased in areas where dredging took place.

We quantified the consequences of these declines by calculating, for each year, the percentage of the intertidal area that would yield insufficient intake rates for

Figure 3.1 Worldwide connectedness: the flyways of the six identified subspecies of red knots (Calidris canutus)
knots to maintain a positive energy balance. In the Wadden Sea, only a limited part of the available intertidal flats is rich enough in suitable prey to be of any use to foraging red knots in the best of years (Piersma et al. 1995; van Gils et al. 2006b). From 1998 to 2002, however, the percentage of one-square-kilometer blocks that were too poor for red knots to obtain a threshold intake rate of 4.8 watts, based on food requirements at that time of year (see Piersma et al. 1995), increased from 66% to 87% (van Gils et al. 2006a). This loss was entirely due to an increase in previously suitable blocks that were dredged; the number of previously unsuitable (and undredged) blocks did not increase.

As a consequence of the widespread dredging in the most biodiverse areas of intertidal flat (Kraan et al. 2007), diet quality in terms of the flesh-to-shell mass ratios declined by 11.7% per year. To compensate for such reductions in prey quality, red knots should increase gizzard mass (Dekinga et al. 2001; van Gils et al. 2003), and they did (van Gils et al. 2006a). This allows them to process the larger amounts of shell material that are necessary in order to maintain a sufficient intake of meat. Despite increasing gizzard size over the years, resightings of individually color-banded birds whose gizzards were measured with ultrasonography before release demonstrated that birds not seen in our study area within a year after release had undersize gizzards; individuals that we did see again had gizzards large enough for a balanced daily energy budget (van Gils et al. 2006a). Local annual survival rate, calculated from resighting rates of banded birds, increased with year-specific food quality. This means that birds arriving from the tundra breeding areas with gizzards that were too small needed more time for their gizzards to adjust than their energy stores allowed them, and thus they faced starvation unless they left the area.

Banded knots that disappeared from our study area may have died or, perhaps more likely for a wide-ranging migrant, emigrated to other areas such as the estuaries in the United Kingdom. Here they probably paid a mortality cost as a result of the extra travel or uncertainties in the food supply at their new destination. Whatever happened to them, the stark decline in numbers of red knots wintering in the Wadden Sea can be explained satisfactorily by these documented population effects of declining food conditions (van Gils et al. 2006a). The local disappearance can also account for much of the 25% decline of the entire Northwest European wintering population over the same period. This leads us to conclude that the industrial forms of commercial exploitation allowed by the Dutch government in one of the country’s best legally protected nature reserves have been directly responsible for the population decline of an also fully protected long-distance migrant shorebird species. Studies on the declines of both another fully protected shellfish-eating shorebird, the Eurasian oystercatcher (Haematopus ostralegus), in the Wadden Sea (Verhulst et al. 2004) and a nearby UK estuary, the Wash (Atkinson et al. 2003), and a strictly molluscivore sea duck, the common eider (Somateria mollissima) (Camphuysen et al. 2002), have reached precisely the same conclusion.

Obeying an order of the European Court that mechanical dredging for cockles is a new economic activity that has to be evaluated in the context, the EU’s Habitats and Birds Directives, the Netherlands State Court (Raad van State) destroyed the existing governmental permits for the procedure issued by the Dutch Ministry for Agriculture, Nature and Food Quality. This forced the ministry to pro-
hibit the mechanical forms of cockle dredging from 2004 onward, and the international companies affected received a generous compensation sum of more than 100 million euros (Wilde Kokkels n.d.). Although this may have meant the end of industrial dredging for cockles in the Wadden Sea, the ministry has since issued new permits for mechanical dredging for lugworms, worked toward an increase in the number of permits for hand cocklers and harvesting intertidal mussels, and failed to examine the degree to which the negative effects of shrimp fishing on bottom communities warrant fresh examination (e.g., Buhs and Reise 1997; Buschbaum and Nehls 2003).

CONCLUSIONS

One of the many factors threatening the ecological integrity of the Wadden Sea is bottom disturbance from fishing, particularly mechanical dredging for shellfish. Because of its far-reaching ecological impacts, it has been a major policy issue for several decades.

In view of the commitments made by the international community to safeguard the flyway populations of shorebirds such as the red knot, the direct and indirect effects of bottom trawling and dredging on intertidal ecosystems are a major concern. The probability that damaged intertidal flat communities will recover has not been determined, but it is likely to be even lower than the probability of the recovery of fish stocks after overfishing (Hutchings 2000). Little doubt exists that the time course of any recovery will be a function of the spatial scale at which the disturbance took place (Lenihan and Micheli 2001). The time constant of general processes in the coastal zone is quite tightly correlated with their specific spatial scale. Given the extent of dredging for cockles on the intertidal flats of the Wadden Sea, the time to the beginning of recovery would be rather longer than a year (Piersma et al. 2001). Using data from the literature for minimum recovery times after disturbance for intertidal and subtidal soft-sediment habitats, we can make a preliminary quantitative assessment of time to the beginning of a recovery; it would be semiquantitative, however, as only datapoints from studies where recovery was positive could be included (Versteegh et al. 2004). Affecting up to 100 square kilometers of intertidal flats, mechanical dredging for cockles alone is predicted to require at least 30 years for full recovery. We regard this as the most optimistic assessment, as recovery times may be much longer still if mechanical dredging moves the intertidal ecosystem toward a different, and much less biodiverse and productive, stable state (Scheffer et al. 2001).

In summary, mechanical dredging for shellfish in the Dutch Wadden Sea has caused long-term ecological damage and led to the loss of shorebird populations dependent on shellfish resources. After dredging, soft-sediment systems are left greatly impoverished in both biomass and biodiversity, with serious negative effects for the birds, fish, and humans living off these coastal ecosystems. Such losses are easy to predict but hard to reverse: large-scale mechanical disturbance of intertidal flats and other sea bottoms has been shown to lead to irreversible, or at least very long-term, negative changes in ecosystem properties. It follows that industrial,
mechanical harvesting methods such as those allowed by the Dutch government in protected coastal nature reserves under its management are unsustainable (Gross 2006). Only handpicking and some limited forms of gillnetting may qualify as sustainable forms of intertidal exploitation.

REFERENCES


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