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Review of the Ecological Effects of Dredging in the Cultivation and Harvest of Molluscan Shellfish

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ABSTRACT

This document reviews effects of dredging associated with the cultivation and harvest of molluscan shellfish, as reported in the literature. Dredges can disturb the structure of the substrate, alter the biological community, and modify sediment biogeochemistry. The rate of recovery subsequent to dredging varies with habitat and sediment type, composition of the resident biological assemblage, and hydrodynamic attributes of the environment. Our goal is to evaluate mechanical and hydraulic dredge harvesting of cultivated oysters and clams from nearshore, leased grounds located primarily along the Atlantic and Gulf Coasts of the United States. In nearshore coastal areas where aquacultural shellfish cultivation is conducted, disturbance from natural processes is frequent, and rapidly growing benthic organisms with short generation times are common. Typically, the duration and spatial extent of shellfish dredging associated with cultivation are limited in scale. These factors, along with the use of sound practices, often mitigate impacts and accelerate ecological recovery after shellfish dredging. Based on our review of the published literature, the physical, biological, and chemical effects of shellfish dredging within the inshore coastal zone are generally short-lived, with the rate of recovery varying among studies.

INTRODUCTION

Dredging, as used in cultivation and harvest of molluscan shellfish, continues to be a topic of discussion among marine resource shareholders. A wealth of information is available concerning shellfish dredging, including bibliographies (e.g., Dieter et al. 2003; Dugas et al.1991; Redant 1987; Rester 2000; Wion and McConnaughey 2000), historical literature and reviews (e.g., Winslow 1882; Nelson et al. 1948; MacKenzie 1997; Wallace and Hoff 2005), and environmental impact statements (e.g., Vining 1978; Barnes et al. 1991). Comprehensive review articles focus on harvesting practices (e.g., Bigford 1997; Beentjes and Baird 2004; Tarnowski 2006), generalized effects of mobile fishing gear (e.g., Stevenson et al. 2004; Løkkeborg 2005; Steele et al. 2005) and environmental implications of bivalve culture (e.g., Spencer et al. 1996, 1997,1998, Bartoli et al. 2001; Olin 2002; ENVIRON 2007). Experimental studies have investigated the effects of harvesting and fishing-related disturbance (e.g., Rumohr and Kujawski 2000; Gilkinson et al. 2005; Morello et al. 2005; Fahy and Carroll 2007). This broad body of scientific and historical literature indicates a strong and sustained interest in effects of shellfish cultivation and harvesting practices on marine environments. Few studies, however, have focused on more contemporary shellfish cultivation methods conducted on leased beds using intermittent dredging.

Many research studies have examined the physical, biological and chemical effects of mechanical and hydraulic shellfish harvesting on seafloor habitats. Field experiments have compared a variety of dredges, locations, substrates, and habitats at differing spatial and temporal scales. Understanding the effects of dredging requires knowledge of the gear-specific impacts on differing habitat types, the frequency and geographic extent of harvest disturbance, and the biological and physical attributes of affected habitats (Steele et al. 2005). Although dredging initially disturbs benthic habitat, the rate and extent of ecological recovery vary widely. Not all harvesting methods and dredge styles produce identical effects on the seafloor and so observed impacts are not always consistent across studies. Early published research on shellfish harvesting does not reflect the modern improvements in fishing equipment and techniques currently used. The diverse range of human activities occurring in the coastal zone can make it difficult to isolate effects of harvesting from industrial, agricultural, and other anthropogenic influences (Blaber et al. 2000). Although efficiency of mechanized shellfish dredging has been well described, the ecological effects on the benthic community are not as thoroughly understood (Thrush and Dayton 2002). Impacts of shellfish dredging can be contradictory when certain effects have both beneficial and detrimental consequences within the benthos (Dorsey and Pederson 1998). For example, while dredging may initially damage certain organisms, others, including scavengers and opportunistic predators, benefit by feeding on exposed prey or by colonizing newly exposed bottom surfaces (Rheault 2008). These complex factors have contributed to the variety of conflicting viewpoints associated with dredging impacts.

This review of the literature addresses the ecological effects of dredging for molluscan shellfish on marine habitats and benthic communities along the Atlantic and Gulf Coasts of the United States. We focus primarily on the nearshore subtidal dredge fisheries for eastern oysters (*Crassostrea virginica*) and hard clams or northern quahogs (*Mercenaria mercenaria*), which are conducted primarily on leased grounds in shallow water (2 – 13m). We have also included information on effects of dredge harvesting of softshell clams (*Mya arenaria*), since this has been well studied. Related studies that illustrate harvest impacts of other molluscan species are also included. This document does not directly address the offshore harvest fisheries for sea scallops (*Placopecten magellanicus*), Atlantic surfclams (*Spisula solidissima)*, or ocean quahogs

(*Arctica islandica*), although they are discussed where relevant. The body of literature available concerning shellfish cultivation, dredging, and fishing disturbance is extensive. However, care should be used when drawing broad conclusions based on results from one discrete study or gear type since research methods and measures used to assess effects of harvesting vary among studies. This review presents a selection of the relevant literature and seeks to provide a comprehensive overview of the risks and benefits associated with shellfish dredging.

Evolution of Shellfish Harvest and Cultivation

Archeological evidence dating as far back as 150,000 years suggests that early subsistence harvest of shellfish may have affected the population structure of marine bivalves and altered near shore coastal ecosystems (Rick and Erlandson 2009). Native Americans hand collected clams and oysters in shallow coastal waters (MacKenzie 1997) and later fished with rakes and tongs from canoes and skiffs to access deeper waters. Oyster gathering by Native American Indians in precolonial times and the resulting shell middens found throughout New England indicate the importance of oysters in the diets of the indigenous people (Ingersoll 1881). There is speculation that hunter-gathers may have increased resource productivity by using primitive aquaculture to cultivate bivalves (Rick and Erlandson 2009). Shellfish harvesting practices have likely modified inshore habitats from their preanthropogenic composition (Simenstad and Fresh 1995). Land-based processes, including farming, deforestation, and pollution, impacted the marine environment before baseline studies of benthic communities structure were conducted (Jones 1992). This implies a longstanding role for humans in habitat and resource management and makes it difficult to say with certainty what represents a predisturbance community in the coastal zone.

Urbanization over past centuries has fundamentally changed water quality in many estuarine ecosystems and affected the North American oyster fisheries. Growth and expansion of human populations along the coastline is directly correlated with the collapse of oyster fisheries in the United States (Kirby 2004). The historic declines in oyster landings observed from 1890-1940 have been attributed to a decreased consumer demand following food-borne illnesses from shellfish, downward national economic trends, and direct impacts to oyster habitat such as increased siltation and extensive dredge harvesting (MacKenzie 2007). Oyster diseases, such as MSX and Dermo, further reduced harvestable natural stocks (Andrews 1984). Extensive oyster dredging in the harvest fishery which occurred from 1860-1920 may have destroyed up to 75% of Chesapeake Bay’s natural oyster reefs (Paynter 1996). Worldwide, as many as 85% of naturally occurring oyster reefs have been lost (Beck et al. 2011). Many factors, including channel and harvest dredging, have contributed to the loss of reef complexity and vertical structure. Currently, 75% of the remaining global catch of wild native oysters originates in the East and Gulf Coast regions of North America.

Early shellfish harvest methods have been modified over the last two centuries (MacKenzie et al. 2002a). European colonists first used treading and short rakes to retrieve clams and oysters from shallow waters. From the 1700-1900s, fishermen relied on hand-operated tongs and rakes for harvesting hard clams (MacKenzie et al. 1997). Although shellfish dredging with gear towed from vessels is the focus of this paper, it should be noted that manual harvest methods are still practiced widely in areas where dredging is impractical or prohibited. For example, intertidal softshell clam fisheries are collected by hand-raking in Maine, New Hampshire, and Massachusetts while bull-raking to harvest hard clams is used by Long Island baymen in New York and quahoggers in Rhode Island. Hand-operated patent tongs, still used today in Chesapeake Bay (Mann et al. 2004), were mechanized in the 1970s by adding a hydraulic piston closing device to increase harvesting efficiency. The history and status of fisheries in the eastern United States have been extensively reviewed by Mackenzie (1997) and MacKenzie et al. (2002a, 2000b).

Increasingly, over the last century, the use of aquacultural cultivation for production of shellfish in leased areas has replaced the direct harvest of natural stocks. Presently, there are two main approaches to commercial molluscan aquaculture in the United States. Some spatially-intensive, shallow-water operations cultivate hatchery- reared seed by using bags, cages or nets to exclude predators. Other more spatially extensive operations rely on natural set or hatchery seed that are planted on leased beds, which are eventually dredge harvested. For example, in Connecticut oyster seed is dredged from estuaries and then replanted on leased grounds to grow until harvest (Getchis et al. 2006). The state also supports a robust hard clam industry, reliant on leased beds (Connecticut Department of Agriculture 2011).

Types of Shellfish Dredging Gear

Contemporary on-bottom shellfish cultivation uses rake-like dredges to harvest planted shellfish seed or to collect naturally recruited stocks from leased beds. Detailed descriptions and illustrations of different types of dredges and description of their evolution are provided by MacKenzie et al. (2002a). Dredges vary in design, dimensions, and weight depending on target species, sediment type, and whether they are harvesting infauna or epifauna. Mechanical or dry dredges scrape the seafloor, while hydraulic dredges use pressurized water systems to first loosen sediments (Hawkins 2006). Shellfish are collected by towing the dredge slowly, usually in a circular progression over the bottom. A conventional mechanical dredge is towed at the end of a line and collects the catch in a chain bag. Hydraulic dredges use water jets to loosen sediments and then remove clams and oysters into a collecting bag as it is towed. Another type of hydraulic dredge uses suction to lift oysters mechanically off the beds (Nelson et al. 1948). Dredge style and fishing methods vary considerably along the eastern seaboard and Gulf Coast corresponding to local harvesting traditions.

Oysters

Mechanical oyster dredges generally consist of a steel frame, a blade with teeth, a tow chain with wire, and a bag attached to the frame which collects the catch (Nelson 1927; NRC 2002; Stevenson et al. 2004). Dredge teeth penetrate soft bottom to capture partially buried epifauna and remove oysters and shell directly from the substrate surface. To perform efficiently, oyster dredges have considerable weight, proper tooth angle, and are dragged slowly over the bottom by the vessel with the proper amount of scope (line length relative to water depth). Oyster dredge efficiency can vary from 7.6-85% depending on substrate type and the size of harvested oysters (Powell et al. 2002). In the collection of seed oysters, the speed and duration of dredge tows are often modified to improve harvest efficiency on differing bottom types (Getchis et al. 2006). Overfilling of the dredge and damage to the bottom can be avoided with a proper awareness of bottom type, water depth, and tidal cycle (Nelson 1927). To improve catch rates and loosen bottom sediments, dredgers often pass over the same area multiple times (Krauter pers. commun.). Oyster dredging represented an improvement over hand harvest since it allows for efficient collection and offloading of the catch, reduced manpower and equipment wear, minimized damage to the oyster crop, and effective control of oyster pests (Nelson et al. 1948).

Suction dredges have been used to collect juvenile oysters and cultch and can be more efficient than traditional oyster dredges. These dredges are used to transplant oysters for growout, to relocate shell and cultch material, and to clean leased grounds of predators (Ismail 1985). Acting as a large vacuum cleaner, hydraulic suction dredges pump water from the sea bottom into a hose and efficiently lift shellfish (Powell and Ashton-Alcox 2004). In the process, surface material is vacuumed up, washed onto a conveyor, screened to remove mud and sand, and then oysters deposited on the boat deck.

Clams

The mechanical (dry), "rocking chair" dredge, was developed to harvest hard clams in the mid-1940s (MacKenzie et al. 2002a) but was eventually replaced by more efficient hydraulic dredges beginning in the late 1950s. High pressure water jets loosen clams from sediments which are collected in a chain mesh bag as the dredge bar passes beneath the sediment surface. Water pressure must be sufficient to loosen clams from the substrate, but not so great that clams are damaged (Jolley 1972). The performance of hydraulic dredges can vary with sediment type, exhibiting greater efficiency when used on sand as compared to mud bottom (Jolley 1972). The manner of fishing, along with the design of the dredge, can determine harvesting efficiency and the degree of seafloor impact (Williams pers. comm. 2009). In Connecticut, typical hydraulic dredges weigh approximately 200 - 400 kg (450 – 900 lbs) and are about 0.6 – 1.0 m (24 – 40 in) wide.

The hydraulic escalator dredge has a conveyer situated alongside the vessel with a sled connected at the front (North Carolina Department of Marine Fisheries 2001), so that as the escalator is lowered to the bottom, the sled can travel across the seafloor. A blade attached to the sled penetrates several centimeters into the sediments and collects the clams as they are dislodged by water pressure. Hydraulic water jets liquefy the sediments and clams are carried by the conveyer belt to the surface for culling, while undersized clams and debris are returned to the water (Adkins et al. 1983). The escalator dredge has a highly efficient collection rate, covers the ground rapidly, and can harvest continuously with little to no damage to market sized animals (Manning 1960; MacPhail 1961ab; Coen 1995). Efficiency of the hydraulic escalator shellfish harvester is affected by towing speed, sediment type and compactness, and hydraulic nozzle angle and height.

Although the hydraulic escalator dredge can be used to harvest oysters and other species, it was first used in Maryland during 1954 for harvesting populations of softshell clams (MacKenzie et al. 2002a) and modified in 1955 to harvest softshell clams in shallow water on Canadian intertidal flats (MacPhail 1961ab). A similar hydraulic clam rake also developed in Canada was used to harvest clams and could be hand operated by fishermen standing in shallow intertidal flats (MacPhail and Medcof 1962). Presently, softshell clam populations in the Chesapeake Bay are at remnant levels and are no longer commercially viable (Homer et al. 2009).

Shallow water "clam-kicking" unique to North Carolina, is used to harvest natural populations of hard clams (Guthrie and Lewis 1982). Hard clams are blown from the bottom by wash from the boat propeller and collected in a towed, heavily chained trawl or dredge. Turbidity and habitat damage associated with clam-kicking is of environmental concern, especially for submerged aquatic vegetation (Peterson et al. 1987; Street et al. 2005).

Wild harvested shellfish

Much larger and heavier hydraulic dredges are used in offshore fisheries to harvest commercially valuable clam species including surfclams and ocean quahogs (Stevenson et al. 2004). For harvesting sea scallops in the offshore waters of George's Bank and the Mid-Atlantic, New Bedford style dredges are commonly used. These dredges are approximately 4.3m (14 ft) in width, can weigh as much as 1 MT (2,200 lbs), and are sometimes fished in pairs (Stevenson et al. 2004). Scallop dredges are steel-framed structures with a cutting bar on the leading edge which rides above the surface of the substrate, kicking up sea scallops and collecting them into an attached bag, commonly made of steel rings (DeAlteris et al. 2000). Scallop dredges operate most efficiently on soft, flat, muddy sediments and are least efficient on firm, uneven, sandy sediments (Currie and Parry 1999). Dredge size, towing speed, and length of tow vary with water depth and scallop density (Stevenson et al. 2004).

Small, light, mechanical dredges have also been used to harvest bay scallops (*Argopecten irradians*) in shallow waters of the northeastern United States, as well as in North Carolina and Florida (MacKenzie 2008). These dredges are designed to remove adult scallops from areas often containing dense submerged aquatic vegetation. Dramatic decreases in bay scallop populations along the East Coast since the mid-1980s have limited commercial dredge harvest.

Historical and Anecdotal Observations on Dredge Harvesting

Historically, opinions on the best methods for shellfish dredging have varied widely. Fishermen who used hand tongs or rakes often considered dredging detrimental to shellfish, while those who operated dredges believed that dredging of the seafloor enhanced the environment for clam and oyster recruitment (Glude and Landers 1953; Manning and Dunnington 1955; Visel 1990b). Rake and tong fishermen believed specifically that dredging activities could injure, smother, or kill shellfish; increase exposure to predation; interfere with successful recruitment; destroy eelgrass; or damage the seafloor (Glude and Landers 1953; MacKenzie et al. 2002b). In contrast, dredge operators felt that bottom cultivation improved seafloor conditions, kept sediment from becoming too compact for habitation by clams, and enhanced bivalve recruitment and growth rates. Anecdotal observations by fishermen have suggested that dredging may be more efficient than hand tonging or raking and results in less shell breakage, mortality, and unintentional burial than manual techniques (Kyte and Chew 1975; Coen 1995). Further benefits of dredge harvesting may include reduced mortality among target species, decreased impact on the benthos, increased catch rates, and reduced labor as compared to nonmechanical collection methods (Coen 1995).

Observations made by shellfish growers can provide valuable data on harvesting impacts and recovery. Harvesters sample the seafloor each time their gear is deployed (Cranfield et al. 1999), a level of effort which exceeds sampling regimes associated with most experimental studies (Dorsey and Pederson 1998). Access to local knowledge held by fishermen allows for a better understanding of habitats when selecting areas for study (Peterson et al. 1995). Frank Dolan, a Connecticut clammer for over fifty years, associated poor clamming and high clam mortality with acidic sediment conditions. He monitored acidity by rubbing clam shells together in a bucket of seawater; formation of a white cloud indicated "sour" or low pH substrate, while shells from healthy beds produced no cloud when rubbed together (Visel 1990a). Dolan indicated that spreading a light coating of shell to remediate or "sweeten" sour bottom could improve setting of shellfish. These anecdotal observations suggest that dredging and adding shell may actively increase pH levels. Dolan also believed that differences in sediment pH can impact shell morphology and observed that clams grown in "sweet" areas exhibited sharp edged shell margins compared to slower growing clams with blunt shell edges found in "sour" areas of little or no shell cover. He found that rotation of shellfish beds, light shelling, and allowing a 5-7 year waiting period before harvest were key elements to good shellfish production (Visel 1990a). He avoided detrimental practices such as early harvest, which exposes small clams to predation, planting in water deeper than 30 ft and cultivating in areas with too much clay. Dolan found cultivation of oysters to be associated with improved growth and enhanced production of hard clams. Interviews conducted with long time clammers and oystermen provide a rich history of observations concerning habitat and resources and suggest that shellfish cultivation may improve bottom environments and increase clam and oyster abundance (MacKenzie 1979; Rice et al. 1989).

Anecdotal evidence suggests that disturbance from large-scale coastal storms is often followed by large natural clam sets, likely because of removal of surface detritus to reveal clean sandy bottom (Visel 2008, 2009). Storms and hurricanes in the marine environment act much like forest fires in terrestrial habitats by facilitating succession from one type of community and habitat to another through wave action and sediment transport. Natural storm disturbance, which washes silt and organics off the seabed, mimics the action of hydraulic dredging (Visel 2008, 2009). Extended periods without benthic disturbance can reduce sediment quality with a corresponding decline in clam populations. The concept of "marine soil cultivation" using dredges, rakes, and tongs has long been advocated by the shellfish industry to loosen and oxygenate sediments and to remediate unoxygenated and heavily silted bottom devoid of clams. A lack of shellfish cultivation in certain coastal areas of Long Island Sound may have resulted in reduced shellfish sets and a loss of potentially harvestable clams and oysters (Visel 1990b). Cultivation efforts which remove silt from cultch may create good settlement habitat for oyster spat and may benefit clam recruitment by increasing sediment pore size to improve water circulation (Visel 2006). Many fishermen believe mud bottoms are detrimental to shellfish and that turning over of oyster shell matrix improves clam and oyster production (Lenihan and Micheli 2000) by promoting settlement of larval shellfish (Coen 1995) and keeping the bottom free of silt and organic matter (Ingersoll 1881; Visel 2006).

Distinguishing Nearshore Shellfish Cultivation from Offshore Harvest Fishing

In the offshore finfish trawling and molluscan dredge fisheries, shared resources are harvested continually from common grounds over a broad geographic area (Northeast Region EFHSC 2002; Cashin Associates 2008a, 2008b). Offshore dredges, which are larger and heavier than inshore hydraulic dredges, affect a greater portion of the seafloor (Hawkins 2006). Harvesting of nearshore cultivated beds with high shellfish densities is generally intermittent and of short duration, in contrast to the wild harvest of shellfish at low densities, which often necessitates a more intensive fishing effort. Biological impacts resulting from finfish otter trawling and scallop dredging are often more evident because these activities are conducted in lower energy deeper water environments where sessile emergent animals dominate (Hill et al. 1999; Kaiser et al. 2000). Deepwater hydraulic dredging for ocean quahogs and surfclams on sand bottom may pose fewer environmental concerns than when conducted on other sediment types (MacKenzie 1982; Wallace and Hoff 2005). For these reasons, the analogy that mobile fishing gear disturbance of the seabed during wild harvest is equivalent to forest clear cutting (Watling and Norse 1998; Baulch 1999; Watling 2005) is not directly applicable to impacts of small-scale nearshore shellfish cultivation, which is typically conducted on leased grounds, where access is limited to the leaseholder and grounds remain undisturbed until shellfish reach market size. Following commercial harvest, replacement of cultch or seed oysters and natural reseeding of clam beds can restore physical structure, enhance habitat productivity, and promote resource sustainability.

Shellfish Dredging Differs from Navigational Dredging

Dredging used to cultivate and harvest shellfish is sometimes confused with harbor or channel dredging projects. These practices are very different and are conducted at vastly different spatial scales. Hydraulic shellfish dredging superficially penetrates the sediment while navigational dredging projects deepen channels and harbors by removing significant quantities of dredge spoils from the seafloor to barges for disposal (Tarnowski 2006; Visel 2008). Shellfish dredging in a given area is usually conducted over hours or days whereas navigational dredging may continue for weeks or months. Short term mechanical shellfish harvesting takes place during daylight hours (Kennedy and Breisch 1973) but navigational dredging can occur around the clock at high levels of intensity. Deep channel dredging is often conducted in highly industrialized zones where sediments are likely to be contaminated. Therefore, harbor dredging and channel deepening projects may potentially result in a greater environmental impact than do smaller scale shellfish dredging and cultivation.

Shellfish Cultivation Similarities to Terrestrial Agriculture

Shellfish dredging can break up hard-packed sediments, just as farmers till fields to turn over and aerate soil (Nelson 1927). Following harvest of clams or oysters, beds are generally left undisturbed for several years or reseeded and not dredged again until the young reach commercial size. This provides much the same benefit as when upland fields are allowed to rest between planting of crops (Ingersoll 1881). When shellfish beds are allowed to remain undisturbed, the temporary alterations in benthic community structure caused by dredging revert to preharvest conditions (Olin 2002).The ecological communities associated with shellfish cultivation may differ somewhat from the initial benthic fauna, just as occurs in traditional agriculture when fields are cleared for replanting (Watling 2005). Although frequent harvest can prevent benthic succession to climax communities (Watling and Norse 1998), the intention of both terrestrial and shellfish farming is to cultivate a particular crop rather than to allow the site to reach a climax community.

Historically, productive shellfish beds are known to support an abundant benthic biota (MacKenzie et al. 1997). Surveys of benthic communities have shown high invertebrate populations and diverse species composition in areas where shellfishing has occurred for more than 50 years (Bigford 1997). Northern quahog clam populations have shown high resilience following harvest-related reductions, attributable to large breeding stocks, successful larval settling, good survival of seed, and low harvesting mortality among juvenile clams (Vining 1978). Shellfish farmers must manage leased bottom responsibly since successful clam farming depends on sustainable harvesting of product (Vining 1978) and healthy seafloor environments.

Scale of Disturbance, Faunal and Habitat Sensitivity, and Gear Considerations

Spatial and temporal scales of shellfish dredging activity are important considerations when assessing the potential impact on habitat. Shellfish cultivation generally occurs on small spatial scales, relative to a much larger surrounding coastal marine ecosystem. Leased shellfish beds typically make up a very small percentage of the total available seafloor of the coastal zone in the United States. For example, in Connecticut, only 9% of the seafloor (77,000 acres) is under lease within the 844,800 acre Long Island Sound. At any given time, much of this leased acreage is not actively fished, reducing the dredging impact further. For these reasons, the short-term, immediate effects of dredging and subsequent ecological recovery represent a series of relatively brief events with impacts limited to discrete portions of the coastal zone. In a review of experimental studies on shellfish dredging, Tarnowski (2006) compares the extent and duration of impacts associated with anthropogenic and natural disturbances to illustrate the wide range of spatial and temporal scales.

Evaluating ecological responses to harvesting disturbance requires an understanding of the sensitivity (the ability of an organism to withstand physical damage) and susceptibility (the probability that an organism will be exposed to damage) of resident organisms as well as an assessment of the intensity (frequency and magnitude) and severity (nature of the impact on the biotic community) of the event (NRC 2002; Tarnowski 2006). Susceptibility of benthic habitats to damage, recovery rate among species, substrate type, time scale, resident biological community, water depth, and presence or absence of vegetation all contribute to the level of dredging impact sustained by the environment (DeAlteris et al. 2000; Barnette 2001; Beentjes and Baird 2004; Cashin Associates 2008a, 2008b; Constantino et al. 2009). Severity is influenced by substrate characteristics, seafloor response to disturbance, faunal and floral sensitivity and distribution, frequency of fishing, gear attributes, and life history characteristics (Kaiser et al. 1989; Langton and Auster 1999; Olin 2002; Rheault 2008; Wilber et al. 2008).

Magnitude of physical disruption to the seafloor is contingent on the type of mechanized harvester as well as depth of gear penetration; frequency of fishing; towing speed; and how the equipment is rigged, modified, and fished (Meyer et al. 1981; Gaspar et al. 1998; DeAlteris et al. 2000; NRC 2002). For example, when gear was properly rigged and catch efficiency was high, clam dredging caused only minor damage and mortality to macrobenthic organisms within a dredge track (Gaspar et al. 2003). Dredge efficiency, which is determined by towing speed, depth of the cutting blade, and hydraulic flow rate, varies with location, bottom type, shellfish density, gear design, weather and operator skill (Jolley 1972; Smith and LeBlanc 1976; Smolowitz and Nulk 1982; Lambert and Goudreau 1996; Hawkins 2006). Pump performance can influence harvesting efficiency since insufficient water pressure fails to effectively remove clams, while too much pressure can be damaging (Jolley 1972). Contemporary hydraulic dredges are highly efficient, collecting up to 90% of clam biomass in a single tow when fishing is optimized (Hauton et al. 2007). The first tow of a dredge is expected to have greater impacts than subsequent passes (Northeast Region EFHSC 2002); however, the effects of shellfish dredging are generally cumulative (NRC 2002).

Effects of Shellfish Dredging Are Variable

Variability in harvesting practices, local environmental conditions, and differing benthic community characteristics explain the broad range of physical, biological, and chemical impacts documented in the literature. Harvesting devices vary in their design and implementation, and seafloor characteristics differ among habitats. Disturbance is seldom consistent across a harvested area since portions of dredged bottom can remain unharvested while others may be worked multiple times (Vining 1978). Systemic dredging of seafloor is difficult because it is impossible to physically mark the exact path travelled by the dredge (Vining 1978). Evidence of mechanical harvest can vary with some areas appearing undisturbed while others are crisscrossed with dredge tracks and depressions (Klemanowicz 1985; Manzi et al. 1985). This may account for differences in the diversity, distribution, and abundance of benthic organisms sometimes observed across dredged zones (Chícharo et al. 2002a) and can complicate assessment of dredging impacts. Variability in performance of mechanized gear during towing may also result in changes to macrofaunal communities that are not uniform along dredge tracks (Chicharo et al. 2002a). An understanding of gear specific effects on various habitat types (experimental studies), frequency and geographic distribution of tows (fishing effort), and physical and biological attributes of the benthos (seafloor mapping) is necessary when evaluating ecosystem effects of dredging (NRC 2002).

Experimentally Measuring Ecological Change

Designing a field experiment to evaluate impacts of dredging or fishing is challenging, since the goal is to detect change in a dynamic system. Impacts are often assessed by conducting experimental dredging and measuring the benthic community response. Data are compared before and after disturbance, against an undisturbed control site, or by comparing experimental results to historical data for that area (Watling and Norse 1998; Johnson 2002; Løkkeborg 2005). Preliminary "before" sampling is used to identify environmental or biological gradients that could complicate analysis and to determine the sampling effort required to detect a given level of change for a variable (Kaiser 2005). Community response is often mediated by the source of disturbance and site-specific factors, such as site history and the inherent ecological plasticity of many benthic species, and these factors can make detection of subtle ecological change difficult (Whomersley et al. 2010). Sampling methods, such as BACI (Before-After and Control-Impact), are used to distinguish natural change from that associated with human activities by statistically assessing and determining the ecological significance of a given impact (Hewitt et al. 2001). The principal assumption of BACI experiments is that anthropogenic disturbance alters an environment so that it differs both from its original state prior to fishing and from concurrent natural changes occurring in control sites (Underwood 1992). When experimentally dredged areas are compared with nearby undredged sites, it is assumed that control and experimental sites are equivalent (NRC 2002). Water depth, substrate type, and benthic assemblages in the experimental site should be similar to those of control areas (Collie 1998). Few areas within the coastal zone remain unaffected by anthropogenic disturbance or fishing activity, and this lack of undredged areas complicates interpretation of harvesting impacts on benthic habitat and marine resources (Kaiser et al. 1998; NRC 2002). Dredge types and designs, disturbance regimes, bottom substrates, natural disturbance levels and biological communities are seldom identical (Løkkeborg 2005), and because each experimental protocol is unique, these differences can complicate comparisons across studies.

Further, the complex nature of field studies can result in experimental design weaknesses. Differences in fishing intensity across a study area can introduce variability, and lack of appropriate experimental replicates can overestimate impacts (Collie 1998). The short time frame of some studies may limit data on recovery, and it can be difficult to relate experimental plots to the spatial and temporal scale of actual dredging disturbance (Hall and Harding 1997; Langton and Auster 1999; NRC 2002; Gilkinson et al. 2003; Løkkeborg 2005). Studies of fishing disturbance and benthic communities should be conducted at a scale relevant to the commercial fisheries (Queiŕos et al. 2006). In studies where recent experimental fishing is compared to historical data, availability of archival information on species abundance and composition prior to disturbance may be limited (NRC 2002). Although time series analysis can assess changes in community structure, distinguishing fishing effects from other environmental or anthropogenic perturbations is not always possible (Kaiser et al. 1998). Natural changes in control or unfished sites can interfere with comparisons against fished areas, and since large temporal and spatial variations occur in nature, anthropogenic disturbances may be masked by more dominant natural processes (Løkkeborg 2005). Benthic community structure maintains some fluidity from year to year because of changes in local conditions which influence reproduction, survival, and recruitment processes, so it may be hard to differentiate these natural variations from dredge-induced effects (Gaspar and Chícharo 2007). Most studies of fishing effects have been conducted in shallow water on small spatial scales, study acute rather than chronic disturbance, look at short term response, and focus on animal communities rather than ecosystem level processes (NRC 2002). The interrelationships among fishing intensity and frequency, fishing methods and gear, seafloor structure, productivity, abundance of economically important species, and community diversity are not easily resolved (Gilkinson et al. 2003). Even when fishing effects are not detected, it cannot always be concluded that no impact has occurred (Løkkeborg 2005).

EFFECTS OF SHELLFISH DREDGING

In the following sections, we review effects as reported in the literature. Dredging effects are divided into broad physical, biological, and chemical categories. Impacts reported here have been compiled from studies conducted under different geographic and environmental conditions, spatial scales, with many types of dredge equipment. For this reason, it is important to consider the specific details and context of each study when drawing general conclusions concerning the effects of shellfish harvest dredging. Some of the relevant research studies examining dredging effects on specific shellfish species and habitats are summarized in an appendix to this document (Tables 1-4). Target species; habitat and sediment type; harvesting equipment used; study location; biological, physical, and chemical impacts; recovery; and author citations are provided for each study. Tables 1-4 provide an ecological and geographic context for research and experimental studies investigating the effects of shellfish dredging. Genus and species names listed in the tables reflect current accepted nomenclature and may differ from earlier versions of scientific names which appear in the original cited literature.

Physical Effects of Dredging

The action of mechanical and hydraulic shellfish dredges physically disrupts benthic substrate. Harvesting may suspend sediment, increase turbidity, alter substrate composition, and cause sediment plumes. Dredges may leave behind tracks of varying depths and widths along the bottom that persist until sediments are restored by natural processes. In the following section we review studies that report specific gear effects and information on the time required for recovery of the physical structure of habitat.

Suspension of Sediment, Increased Turbidity, and Sediment Plumes

Shellfish harvesting can have a direct effect on water quality by suspending sediments and increasing water column turbidity (Dayton et al. 1995; Johnson 2002: Morgan and Chuepagdee 2003; Rheault 2008). Hydraulic dredges use water jets to liquefy the substrate, dispersing fine silt and clay into the water column, elevating turbidity, and creating a sediment plume downstream of operations (Kyte and Chew 1975; Kyte et al. 1976; Coen 1995; Barnette 2001). Sediment disturbance appears greatest near the conveyer belt and water jets where substrate material is returned to the bottom (Kyte and Chew 1975). Elevated turbidity and sediment plumes may extend 75-100 ft beyond the dredge zone (Manning 1957; Haven 1979; Manzi et al. 1985; Maier et al. 1998), transporting and redepositing sediment into adjacent areas (Vining 1978). In most cases, suspended solids returned quickly to low values moving away from dredge activity (Kyte et al. 1976; Maier et al. 1998) with 98% resettlement occurring within 50 ft (15m) (Rheault pers. commun. 2010). Suspended sediment dispersed during suction dredging returned to background levels within 40 m of harvest activity (Spencer 1997). Effects of sediment dispersal, turbidity, and plume formation appear to be transitory as most plumes dissipate within a few hours of dredging (Maier et al. 1998). Occasionally, sediment may remain unsettled for a more extended period after cessation of dredging (Ruffin 1995; Tarnowski 2006).

Particles suspended in plumes dissipate exponentially over time, rapidly at first as heavy coarse sediments (pebbles, shell fragments, coarse sand) settle out, followed by progressively smaller particles (medium to fine sand) and lastly silt and clay (Goodwin and Shaul 1980; Ruffin 1995). Larger sand particles are redeposited near the dredge while measurable amounts of fine silt and clay particles remain in suspension and may be carried away by currents (Godcharles 1971; Tuck et al. 2000). Sediment grain size, wave activity, current levels, and water column depth all determine the initial turbidity, light attenuation, size, and dissolution of dredge plumes (Ruffin 1995; Tarnowski 2006). Substrate type can determine the amount of suspended solids in a plume and how long it persists, while the distance and direction of the plume is primarily controlled by water currents (Tarnowski 2006). The volume of displaced sediment determines the concentration of suspended particles. Mechanized harvesting can increase siltation at lower depths (Rothschild et al. 1994; Breitburg et al. 2000; Street et al. 2005) by winnowing of fine sediments by strong currents and wave action (Cranfield et al. 1999). The largest plumes, highest turbidity, greatest light attenuation levels, and slowest plume decay rates are generally produced in shallow water environments containing high silt and clay content (Ruffin 1995; Tarnowski 2006).

Suspension of sediment by dredging can affect many aspects of the benthic environment. Suspended sediment and turbidity plumes temporarily degrade water quality and intensify bottom siltation (Cashin Associates 2008a, 2008b). Turbidity transports and redistributes substrate material (Kyte and Chew 1975; Manzi et al. 1985) resulting in reduced water clarity (Watling and Norse 1998). Dispersed sediments may take 30 min-24 h to resettle (Lambert and Goudreau 1996; Northeast Region EFHSC 2002). Compared to long-term, natural wind-induced suspension of sediments and nutrient loading from land runoff, release of suspended sediments during dredging can be relatively minor (Auster and Langton 1999). Localized effects can, however, be more significant where low dissolved oxygen levels occur and reduced substances become resuspended. Natural turbidity levels generated by wind and tides can produce particle loads equaling or exceeding that of dredging disturbance (Tarnowski 2006) which are generally tolerated by organisms inhabiting dynamic inshore environments. In the Thames River of Connecticut, sediment suspended during storm events exceeded that of navigational dredging projects by an order of magnitude (Bohlen et al. 1979). The impact of smaller scale shellfish dredging would be even less significant, as bottom disruption is limited to a more discrete area than that impacted by either coastal storms (Wilber and Clarke 2001) or navigational dredging.

Disruption of the Sediment Surface

Movement of dredges across substrate or through the sediments has the potential to reduce bottom roughness, smooth surface topography, damage sedimentary bedforms, scar the seabed, and modify the physical environment (Pranovi and Giovanardi 1994; Dorsey and Pederson 1998; Langton and Auster 1999; DeAlteris et al. 2000; Emmett 2002; NRC 2002; Morgan and Chuepagdee 2003; Willner 2006). Dredging can erase structural features from the seafloor and remove burrows, tubes, and shells through destruction, burial, or sedimentation (Gilkinson et al. 2003; Hauton et al. 2003a). Mobile gear which scrapes the seafloor can reduce habitat complexity by diminishing vertical and three-dimensional structures (Watling and Norse 1998; NRC 2002; Morgan and Chuepagdee 2003; Rheault 2008). Initial harvesting effects can be significant when the upper layers of the substratum and overlaying fauna are removed and seafloor topography becomes physically altered by the dredge (Kaiser et al. 1989). Substantive changes to physical structure can include smoothing of sand ripples, waves, and ridges (Northeast Region EFHSC 2002). Hydraulic harvesting equipment can resuspend the top sediment layers and bring up deep anoxic material from the bottom (Badino et al. 2004). Water jets from hydraulic dredges penetrate into the sediment releasing trapped gases, resorting sediments, and creating tracks along the bottom (Bigford 1997). The large volume of water channeled through hydraulic dredges to fluidize the seabed can disrupt the physical nature of the seafloor (Hauton et al. 2003a), create linear tracts of fluidized sand, suspend silt into the water column, and can vertically homogenize the seabed to a depth of 20 cm (Hauton and Paterson 2003).

Dredging activities can cause sediment mobility and instability, creation of spatial patchiness, and increased sediment load (DeGrave and Whitaker 1999). Sediment loosening, emulsification, and loss of vertical stratification can cause displacement of substrate in harvested clam beds (Goodwin and Shaul 1980). Seafloor sediments can experience increased sediment porosity and reduced compaction for up to a year after dredging (Pfitzenmeyer 1972a, 1972b). Dredging may create transient sand bars which decrease substrate compactness and stability on intertidal flats (Goodwin and Shaul 1980) and in deeper offshore waters (Smolowitz and Nulk 1982). Dredging may change the appearance and texture of bottom sediments with a reduction in the silt-clay component (Haven 1979) or may cause a shift in sediment type (Hauton et al. 2003b). Hydraulic suction dredging has been shown to alter sediment composition in muddy sand locations (Ismail 1985). Suspension of fine sediment results in qualitative as well as quantitative changes to the bottom with a net loss or redistribution of organic matter (Kyte and Chew 1975). Extended intensive harvesting may result in a long term shift in bottom composition (Tarnowski 2006) by increasing grain size and sorting coefficients (Fahy and Carroll 2007). Although horizontal movement of particles can result in their permanent relocation away from the point of origin (Dorsey and Pederson 1998), most material displaced by dredging resettles within 50 ft of the harvest zone (Rheault pers. Commun. 2010). In cases where medium and fine sand dominated, no differences in grain size were observed after harvest (Pfitzenmeyer 1972a).

Changes to Sediment Composition

Shellfish harvesting can potentially alter the morphology and texture of seafloor sediments (Constantino et al. 2009). Dredging causes visible changes to sediment particle size, type, structure, stability, and processing (Kaiser et al. 1989; Pranovi and Giovanardi 1994; Dayton et al. 1995; Simenstad and Fresh 1995; Emmett 2002; NRC 2002; Willner 2006). Impacts of mechanized harvest are highly dependent on sediment composition since sedimentation rates vary in relation to many factors, including particle size. Resuspension and dispersal of fine particles can cause long term effects on sieve fractions (Pranovi and Giovanardi 1994) and decrease the clay portion of the sediment (Maier et al. 1998). Hydraulic escalator dredging of some sand flats can suspend and disperse finer sediment fractions from worked areas (Kyte and Chew 1975), leading to a relative increase in larger grain sizes and a change in the sorting coefficients (Pranovi and Giovanardi 1994; Pranovi et al. 1998; Fahy and Carroll 2007). Hydraulic dredging in Chesapeake Bay resuspended and dispersed fine particles but had no major effect on sediment grain size or structure in areas where medium and fine sand dominated (Pfitzenmeyer 1972a, 1972b). Clam dredging has been shown to completely disrupt sediments by changing them from rich organic sand to coarse sand with broken shell (Moore and Orth 1997). Larger sediment particle size may be more typical of the predisturbance benthos prior to the addition of fine organic silt input from anthropogenic sources such as deforestation, agriculture, and sewage input (Rheault pers. commun 2010). Dredging can also modify hydrodynamics, changing erosional and depositional processes at the sediment water interface (Thrush and Dayton 2002), affecting patterns of water flow and altering environmental parameters such as temperature and salinity regime (Simenstad and Fresh 1995; Emmett 2002). High frequency of clam fishing by mechanical harvest in the Venetian lagoon in Italy was shown to prevent consolidation of sediments (Aspden et al. 2004). Conversely, in Narragansett Bay, RI, one time experimental hydraulic disturbance of the bottom did not significantly alter grain size characteristics or water content of sediments (Sparsis et al. 1993).

Creation of Trenches and Dredge Tracks

Hydraulic dredging can cause visible trenches along the seafloor; redistribution of dredged material; altered substrate composition; and creation of deep, wide and curvilinear furrows while the magnitude of these changes is largely determined by sediment type (Kyte and Chew 1975; Gilkinson et al. 2003). In southern Portugal, passage of a clam dredge over the bottom can produce a depression 30 cm wide and 10 cm deep (Constantino et al. 2009). The seafloor may appear undulating and wavy across the directional axis of dredge tracks with the formation of troughs and ridges (Drobeck and Johnston 1982). Dredge furrows within the tow path are often accompanied by sediment slumping along the sides of depressions (Falcão et al. 2003). Dredge tracks and trenches are sometimes hard and sharply defined with spoil heaps and clay chunks (Kyte et al. 1976; Pranovi and Giovanardi 1994) or may have sharply angled walls and a flat floor (Meyer et al. 1981). Crumbling of track shoulders and erosion by tidal currents can extend track widths. Escalator dredge harvest can dig deep trenches that crisscross the surface, leaving deep holes, mounds composed of side castings, and scattered empty shell along the trenches (Adkins et al. 1983). Poorly operated clam dredges may act like a snow plow pushing clams and sediment to the sides (Meyer et al. 1981) so that windrows of sediment and organisms form along either edge of the trenches (Northeast Region EFHSC 2002; Wallace and Hoff 2005). Formation of a sand buffer at the mouth of certain dredges can push sediment sideways affecting macrofauna differently over the dredge track (Chícharo et al. 2002a). Material removed from the bottom by the dredge and redeposited as spoils in and around the trenches can remain softer than before dredging and may be less firm than bottom in nearby undredged areas (Kyte et al. 1976). Sediment within trenches and/or tracks may be softer, less compact, and vertically stratified for months after dredging (Vining 1978). Sediment in dredge tracks can remain fluidized for an extended period even after the trenches start to refill (Tuck et al. 2000).

Persistence of Dredge Tracks

Studies show variability in the time required for dredge tracks to resolve but in most case trenches and tracks created by harvesting dissipate quickly. Trenches are partially backfilled when heavier clumps of material and resuspended sediment fall off the back of the dredge during harvesting operations (Tarnowski 2006). Physical recovery from dredging tends to be very site specific and tied closely to sediment composition. For example, dredge tracks on sandy bottom can diminish within 24-h (Gaspar et al. 1998, 2003). Dredge tracks may persist as a series of shallow depressions (Meyer et al. 1981) or leave deeper marks which remain for days (Gaspar et al. 2003) or weeks (Manning and Dunnington 1955). Erosion and wave action can reduce the depth and width of dredge tracks within a month of dredging (Hauton et al. 2003a). Escalator dredging in Virginia created trenches 6-8 in (15.4-20.3 cm) deep which resolved in a 1-2 m period (Haven 1979). Ten months after hydraulic escalator harvest in Maine, a complete stratum had reformed, trenches had refilled, and a fine layer of soft sediments had settled in the tracks (Kyte et al. 1976). Following escalator clam harvest in Florida, tracks remained visible up to 86 days (Godcharles 1971). Also, there was no evidence of permanent relocation of suspended sediment or changes to sediment grain size. Physical evidence of hydraulic harvest dissipated within 40 days of dredging in Scotland (Hall et al. 1990). Trenches began refilling within 5 days of hydraulic dredging, and by 11 weeks they were no longer obvious at a site in England (Tuck et al. 2000). Seven months after suction dredging at another English site, sediment structure was nearly restored via natural sedimentation processes (Kaiser et al. 1996). Also in the United Kingdom, trenches created by suction dredging dissipated naturally within a 3-4 m period (Spencer 1997). Dissipation of dredge tracks can also be depth dependent. Clam dredge tracks in a Portuguese study were no longer distinguishable after 24-h at 6 m depth but remained visible for 13 days at a depth of 18 m (Constantino et al. 2009).

The time required for a trench to return to preharvesting conditions depends on natural sedimentary processes (Vining 1978). Hydrodynamics and substrate characteristics of the environment influence the persistence of dredge tracks. Sediment type, grain size, water depth, wind, presence of algae or seagrass, wave action, currents, tides, storm events, and location in the subtidal or intertidal zone all influence how long tracks remain visible (Manning and Dunnington 1955; Godcharles 1971; Northeast Region EFHSC 2002; Hauton and Paterson 2003; Gaspar et al. 2003; Morello et al. 2006; Tarnowski 2006; Thorarinsdóttir et al. 2008). Trenches can persist from hours to years as a function of the erosional characteristics of a site (Northeast Region EFHSC 2002; Tarnowski 2006). The temporal scale of effects is also influenced by the background energy of the environment so that recovery may take days in high energy environments and months in low energy areas (Northeast Region EFHSC 2002; Wallace and Hoff 2005). Dredge tracks remain for longer periods where there is reduced potential for erosion because of lower currents and less wave energy.

In some cases, tracks and trenches created by dredging alter the sea bottom for a longer period (Kyte and Chew 1975). Depressions left behind by dredging in estuaries may sometimes take up to a year to refill (May 1973). Although no longer visible in video images, hydraulic clam dredge furrows on the deep offshore Atlantic Scotian shelf were still detectable by sidescan sonar one year after dredging, showing a gradual degradation of furrow margins through slumping, active transport, and bioturbation (Gilkinson et al. 2003). According to acoustic reflective sonar, comparisons between dredge furrows and the surrounding seabed indicated a long term change to sediment structure. One year after escalator harvest in Maryland, the seafloor exhibited less compaction of sediments (Pfitzenmeyer 1972a), increased porosity, and softer substrates (Pfitzenmeyer 1972b). Another study of hydraulic escalator harvesting conducted in Florida found differences in sediments between dredged and adjacent areas were no longer detectable after 1y (Godcharles 1971). Sediment has been shown to return to predredging substratum within a year of oyster dredge harvest in Florida (Simon and Connor 1977). In a review of environmental effects of bivalve aquaculture, Olin (2002) suggests that changes in sediment structure associated with shellfish dredging are reversible and readily dissipate over time.

Effects of Dredging on Adjacent Undredged Areas

Suspension and redistribution of sediments from dredging can impact organisms living some distance away from the harvested area (Kyte and Chew 1975). In one study of the offshore clam fishery on the Atlantic Scotian Shelf, burrow structures made by benthic organisms declined in both hydraulically dredged and nearby unworked areas (Gilkinson et al. 2003). However, many nearshore studies have shown no impact of dredging outside the dredged area. Shellfish dredging in Virginia and Washington State did not impact adjacent unharvested eelgrass beds negatively (Moore and Orth 1997; Goodwin and Shaul 1980). Downstream from escalator harvesting activity in Maryland, the impact zone appeared limited, and oysters and cultch material remained undisturbed (Drobeck and Johnston 1982). No detrimental effects of siltation were observed on live oyster beds located adjacent to shellfish dredging during studies in Florida and Maryland (Ingle 1952; Manning 1957). Uniform redistribution of sediments caused by dredging did not appear to smother nearby benthic organisms during studies conducted in England and Florida (Schroeder 1924; Spencer et al. 1998). These studies suggest that in general, harvesting impacts are limited to the directly disturbed area.

Harvest of Fossil Shell for Use as Cultch Material

Dredge harvesting is sometimes used to uncover buried fossil shell and bring it to the sediment surface where it can be redistributed as cultch to increase bottom complexity and provide settlement substrate for larval oysters (Manning 1960; Haven 1979; Goodwin and Shaul 1980). Hydraulic dredging may be among the least harmful ways of recovering and processing natural cultch shell since the process produces only minor and transitory changes to the physical and biological environment (May 1973). Mining of fossil oyster shell and effective redeployment can improve spat recruitment and has been considered useful in shellfish restoration efforts (Rothschild et al. 1994).

Biological Effects of Dredging

Many research and experimental studies have been conducted to better understand the biological effects of dredging. Collie et al. (2000) used a meta-analysis of 56 previous experimental studies to quantitatively compare relative levels of impact on benthic organisms across gear types, period of disturbance, scale, region of the study, depth, and habitat type. Among these factors, gear type, region, and taxonomic class had the greatest influence on effects to the benthic biota. The impact of shellfish dredging on benthic organisms is species-specific and largely a function of their particular biological characteristics and the physical habitat. Level of impact resulting from hydraulic or mechanical dredges is determined by an organism's relationship to the substrate (i.e., infauna or epifauna,), its activity level (i.e., mobile or sessile), and inherent structural morphology (i.e., soft-bodied or hard-shelled). Hard clams and oysters that can close their shells tightly are less vulnerable to dredging than are other mollusks with shells that gape. Damage to bivalves often varies depending on shell thickness and burrowing depth (Hauton et al. 2003a). In the following section we review effects of shellfish dredging on marine fauna and flora as reported in the literature.

Mortality and Damage in Benthic Organisms

When dredges move along the seafloor or liquefy sediments, surface dwelling organisms can be removed, crushed, buried, or exposed (Dayton et al. 1995; Watling and Norse 1998). Tubes and burrows may be scraped away and erect and sessile organisms removed from the substrate surface (Dayton et al. 1995; Watling and Norse 1998; NRC 2002). Direct burial and/or smothering of infaunal and epifaunal organisms is possible because of increased sedimentation rates (Coen 1995; Barnette 2001; Morgan and Chuepagdee 2003). Clam and oyster harvesting can result in direct mortality when shellfish pass through or under the dredge, and indirect mortality can occur when shellfish are caught in the dredge, washed out, or discarded (Beentjes and Baird 2004). Mortality of target shellfish can result from gear impact, pressure inside the net bags, surface anoxia, or temperature effects (Alves et al. 2003). Dredge induced mortality can include clams cut or crushed by the dredge blade or assembly (Meyer et al. 1981). Higher postdredging mortality has been associated with low catch efficiency (Gaspar et al. 1998). Increasing dredge efficiency by extending tooth length has reduced the number of injured clams, while prolonged tow length has a higher risk of damaging animals. During the 1960s in Long Island Sound, a minor modification of the tooth angle of oyster dredges from perpendicular to a 15º angle minimized damage and mortality to shellfish seed (MacKenzie 1970).

The number of clams injured by hydraulic dredge harvesting is proportional to increasing water pressure (Moschino et al. 2002). Sorting processes and water pressure can significantly elevate shell damage and stress among clams, especially in commercial sized animals (Moschino et al. 2002, 2003). Levels of biological damage correspond to sediment type and are often greater in fine sand areas as compared to coarser sand sites (Moschino et al. 2002). Shellfish have demonstrated resilience to dredge induced shell damage. Oysters show a capacity for rapid repair of minor shell chipping or abrasions from dredging (Powell et al. 2001), while clams have been shown to experience low mortality and minimal injury after harvest collection (Glude and Landers 1953; Smolowitz and Nulk 1982; Coen 1995).

Effects of Suspended Sediment on Marine Organisms

When sediments are disturbed, turbidity increases as fine-grained materials are resuspended into the water column (Maier et al. 1998). If large amounts of sediment are resuspended at high concentrations and exposure is chronic, impacts can be severe. Under extreme conditions of turbidity, visual feeders and photosynthesizing plankton may be disturbed (Watling and Norse 1998). Discolored water can reduce primary productivity thereby limiting numbers of macroscopic benthic organisms (May 1973). In some cases, turbidity can interfere with normal respiratory and feeding functions in benthic dwellers and result in hypoxia or anoxia (Morgan and Chuenpagdee 2003). Sediment resuspension can potentially reduce the survival of bivalves and fish from gill clogging or by inhibiting their movements and/or burrowing activity (Dorsey and Pederson 1998). Small organisms and immobile species caught in suspended sediment can potentially smother as a result of sedimentation (Manning 1957). Redistributed sediments can rebury shell and cultch material making it unavailable to other organisms for settlement or refuge (Tarnowski 2006). However, most species found in shallow coastal waters where harvesting is conducted can be expected to tolerate extended periods of turbidity (Gaspar and Chícharo 2007). Studies of mechanical clam harvesting in South Carolina creeks showed no significant effect of short term elevated turbidity on bottom dwelling invertebrate and finfish assemblages (Maier et al. 1998).

A review by Wilber and Clarke (2001) identifies the acute effects of suspended sediment exposure on fish and shellfish associated with navigational dredging. Laboratory bioassays exposed target organisms to suspended sediment at increasing concentrations and exposure durations until responses were measured. Survival of fish and shellfish varied with dosage from no effect to 100% mortality. For example, in a 2-day exposure at a relatively high sediment level of about 10,000 mg/l, the effect on larval bivalves ranged from sublethal to 75% mortality. Since the degree of sediment resuspension is proportional to the duration and magnitude of dredging, short term intermittent shellfish harvesting would likely have less of an effect than navigational dredging.

Immediate Initial Reduction in Benthic Organisms

Mechanical harvest may remove or spatially redistribute target and nontarget meiobenthic and macrobenthic organisms resulting in decreased abundance, number of taxa, evenness, biomass and/or diversity, and possibly altered community structure (Alves et al. 2003; Constantino et al. 2009). After hydraulic clam dredging, a short term nonselective reduction in species number, biomass, and abundance of infaunal organisms has been observed, with the greatest declines occurring inside dredge tracks (Simon and Conner 1977; Connor and Simon 1979; Ismail 1985; Hall et al. 1990; Provani and Giovanardi 1994; Tuck et al. 2000; Gilkinson et al. 2005). Organisms may be captured directly in dredges or resuspended in the sediment plume and transported away by water currents (Pranovi et al. 1998). The physical action of the dredge removes macrofauna and smaller organisms such as polychaetes and amphipods (Kyte and Chew 1975) by resuspension, and/or advection (Gilkinson et al. 2005).

Some studies which documented an initial decline in species abundance and biomass, also observed rapid benthic community recovery. For example, declines in benthic organisms immediately after dredging were of short duration on subtidal clam beds in Washington State (Goodwin and Shaul 1980). Harvesting of manila clams (*Tapes philippinarum*) by hand raking and suction dredging caused a 50 and 90% initial reduction, respectively, in species diversity and abundance within an aquaculture site located in the River Exe, in Devon, United Kingdom, with recovery of the invertebrate community within 8 m of harvesting (Spencer 1997). Experimental water jet dredging in Scotland caused an immediate decline in species number, biomass, and number of individuals within the dredge track but this was no longer significant after 5 days (Tuck et al. 2000).

Effects Vary with Faunal Composition

Dredging and other types of seafloor disruption can alter the variety and abundance of organisms. Responses of the biological community to shellfish dredging are species-specific (Kyte et al. 1976) and can be difficult to quantify depending on whether affected organisms are hard bodied like clams or soft bodied like polychaetes (Wallace and Hoff 2005). Dredging removes large bivalves and epibenthic organisms from dredge tracks, leaving smaller thick-shelled animals intact while damaging fragile thin-shelled bivalves and polychaetes (Hauton et al. 2003a). Epifauna inhabiting the substrate surface experience greater disruption from dredging than do infaunal organisms which dwell within sediments (Drobeck and Johnston 1982). Some studies have found soft bodied, deposit-feeding crustaceans, polychaetes, and ophiuroids to be the most affected by dredging activities (Constantino et al. 2009). For example, in Scotland, water jet dredging decreased polychaete populations while amphipod numbers increased (Tuck et al. 2000). In a Maine study, numbers of amphipods and polychaetes were immediately reduced by dredging (Kyte et al. 1976). Amphipods were least affected, bivalves most affected, and polychaetes and ophiuroids moderately affected in a Florida dredging study (Simon and Connor 1977; Connor and Simon 1979). The greater mobility of amphipods and the attraction of predators and scavenging species to the disturbed benthos inhabited by polychaetes may account for observed differences in dredging impacts among these species (Tuck et al. 2000).

Dredging can impact benthic community structure (Smolowitz and Nulk 1982; Dayton et al. 1995; Pranovi and Giovanardi 1994; DeAlteris et al. 2000; Emmett 2002; Johnson 2002; NRC 2002; Willner 2006) and population dynamics (Cranford et al. 2006) by increasing abundance, diversity, and biomass of some benthic invertebrates and by decreasing biomass and species richness among others (Dorsey and Pederson 1998; Morgan and Chuepagdee 2003; Rheault 2008). Benthic community structure changes when fishing activities disrupt physical habitat, add food or nutrients to the benthos (in the form of discarded organisms), or reduce or remove populations at certain trophic levels (Blaber et al. 2000). In an Italian coastal lagoon, bottom sediments modified by hydraulic dredging activity showed altered community composition (Pranovi and Giovanardi 1994). Dredging resulted in a shift among the dominant organisms within a muddy marl substrate in Ireland (DeGrave and Whitaker 1999) where 6 m after dredging, omnivorous crustaceans became more plentiful in the dredged area while filter feeding bivalves were more abundant in the control site. High intensity hydraulic dredging in the Adriatic Sea resulted in dominance of a few organisms, but the number of species began to increase as fishing intensity declined (Morello et al. 2006). Changes to the physical environment can reduce the value of benthic habitat for certain species (Langton and Auster 1999) and force some species into suboptimal environments (NRC 2002) while other species may benefit. For example, dredge-induced resuspension of organic matter increased numbers of clams in affected areas of Italy (Pranovi et al. 2003). Hydraulic clam dredging can alter ambient community structure when target species decline and are replaced by opportunistic colonists (Fahy and Carroll 2007). Lack of sediment consolidation after mechanical clam harvest may inhibit biological community succession and establishment of stable benthic assemblages (Aspden et al. 2004). Many benthic animals will not reestablish in a dredged area until sediment stability has returned (Goodwin and Shaul 1980). However, shellfish dredging does not always measurably alter density or species composition among small benthic macroinvertebrates because of their short life spans and capacity for rapid recolonization (Peterson et al. 1987).

Shell Damage to Bivalves Caused by Dredging

Since mechanical harvesting requires physical collection and processing of shellfish, a potential for handling damage exists (Nelson et al. 1948). When hydraulic dredging brings large numbers of clams to the surface, shells may be chipped or broken (Gilkinson et al. 2005). Razor clams collected by suction dredge from Mallow Bank in the Bay of Ireland contained sand grains embedded within clefts in the shell matrix, presumably sustained during previous dredging events (after which they had been returned to the bottom) or while escaping dredge capture (Robinson and Richardson 1998). Injury to clams appears inversely proportional to catch efficiency or the ratio of number of clams entering the dredge to the number found along the dredge path (Gaspar et al. 1998). Damage to surfclams from hydraulic dredging is considered a function of water pressure, blade height, and towing speed (Lambert and Goudreau 1996). When mechanical harvesters are operated improperly or at low efficiency, some mortality of target bivalve species and other shellfish has been observed (Nelson 1927; NRC 2002; Morgan and Chuepagdee 2003).

Conversely, some studies of hydraulic dredging have shown little breakage or mortality among juvenile and adult clams as a result of burial, failure to reburrow, or predation (Manning and Dunnington 1955; Manning 1957; Vining 1978). Only a small fraction of softshell clams dredge harvested in Maine were found to experience injury (Kyte et al. 1976). Less than 1% of clams dug with a mechanical shellfish-digger (early hydraulic conveyer dredge) were damaged in Canada (Dickie and MacPhail 1957). Contemporary mechanical harvesting in South Carolina documented minor damage to the shell matrix among 5% of harvested oysters (Collier and McLaughlin 1984). Repeated dredging of oysters in Delaware Bay resulted in only minor chipping and abrasion of shell (Powell et al. 2001).

Dredging Effects Vary with Clam Size

Generally, smaller clams demonstrate a greater resilience to water pressure and sorting associated with hydraulic shellfish harvesting than do commercial-sized animals (Pfitzenmeyer 1972a). No significant reduction was observed in populations of clams < 35 mm shell length after commercial harvesting in the Adriatic Sea (Moschino et al. 2002, 2003). Ninety percent of small softshell clams < 2 in, collected by Maryland escalator dredge, fell through the conveyer mesh and were returned to the bottom within 100 ft (30.48 m) of the point of entry (Medcof 1961). Most clams reburied quickly with fewer than 10% experiencing damage. Hydraulic escalator dredging of oysters showed no measurable detrimental effect on juvenile softshell clam populations in Maryland (Drobeck and Johnston 1982).

Temporary Decline in Commercially-Sized Shellfish

Shellfish dredges are typically designed to harvest bivalves of a particular size for market. Harvesting of commercial-sized shellfish temporarily reduces the number and biomass of adults of the targeted bivalve species (Rice et al. 1989; Gilkinson et al. 2005). Hydraulic escalator dredging for softshell clams in Maine resulted in an immediate decline in commercial sized clams within the harvested area (Kyte et al. 1976). Shellfish dredging in the United Kingdom reduced overall densities and mean length of remaining clams through preferential removal of commercial-sized animals (Robinson and Richardson 1998), although such population reductions are generally short term (Morgan and Chuepagdee 2003). Fishing activities decrease the abundance, change the age structure, and modify the size composition of the target species (Blaber et al. 2000). Although harvesting in Washington State significantly reduced numbers of commercial clams, abundance of smaller seed clams remained unaffected (Goodwin and Shaul 1978).

Sediment Type Affects Biological Effects

The magnitude of dredging impact on benthic organisms is often a function of sediment type. Clams in fine grain sand generally experience more damage than those on coarser sand (Moschino et al. 2003). Fauna in stable gravel, mud, and biogenic habitats are more adversely impacted by fishing activities than those in less consolidated coarse sediments (Collie et al. 2000). Mortality of clams in Canada was greater in compact clay sediment than in clay silt (Medcof and MacPhail 1964), while clams living in fine sand showed higher damage levels and more impaired individuals than those within coarse sand areas of the Adriatic Sea (Moschino et al. 2003). High energy sandy habitats with low to moderate complexity can be resistant to disturbance and show fewer changes in abundance and biomass of organisms following trawling and dredging activities (Link et al. 2005). Infauna which inhabit sandy and shallow areas are morphologically and behaviorally adapted to dynamic environments and show little long term impact from dredging, aside from an initial dispersal of organisms (Tuck et al. 2000). Experimental studies of disturbance in shallow sandy environments indicate that changes in community response are generally short term (Kaiser et al. 1998).

Alterations in particle size and texture may change the type of organisms residing in benthic communities (Pranovi and Giovanardi 1994; Skilleter et al. 2006), since sand and mud bottoms support very different species assemblages. Species distribution and abundance of benthic biota are strongly associated with the suitability of the substrate type. For example, clam density is often inversely related to the amount of clay contained in bottom sediments (Nickerson and Brown 1979). Changes to sediment grain size may make a habitat more or less suitable for resident organisms. Hydraulic escalator harvesting can alter sediments and habitat can be either improved or degraded (Kyte and Chew 1975). Often topography and original sediment characteristics must be restored before the biological community returns to its predisturbance composition (Boyd et al. 2005).

Effects of Dredging on Oyster Reef Habitat

Over time, shellfish dredging has modified traditional oyster reef habitat from thick beds of oysters to thinner layers distributed over fine sediments. Long term harvesting of oysters in Chesapeake Bay, first by hand and later with dredges, leveled the profile of oyster bars, contributing to a reduction in oyster productivity (Rothschild et al. 1994). Dredging of historic oyster beds lowered reef heights, elevated sedimentation rates, increased mortality, damaged shells, and expanded reef diameter by spreading shell (Lenihan and Peterson 1996, 2004). Reduction in the height of oyster reefs can alter hydrodynamics and impact oyster recruitment, growth, and survival (Lenihan and Peterson 1996). Leveling of shellfish beds can result in broken valves and mortality of oysters (Winslow 1882; MacKenzie 2007). Removal of substrate by oyster dredging can scatter shells and oysters into less suitable locations, reduce the number of spawning adults, eliminate settlement area for spat, lower disease resistance, and reduce substrate complexity of established reefs (Breitburg et al. 2000; Barnette 2001; Street et al. 2005). The morphology of oyster reefs can be altered by improper or excessive dredge harvesting if dredging occurs too frequently or if equipment is too heavy, resulting in oysters that may become weak and thin, close up, stop feeding, and lose weight (Nelson 1927). Removal of shell or substrate and/or heavy siltation can create a suboptimal environment for oyster growth and survival (Rothschild et al. 1994; Powell et al. 2001). Large amounts of suspended sediment can overwhelm the filter feeding capacity of oysters, stressing or smothering them (Barnette 2001). When hydraulic suction dredging preferentially removes juvenile oysters and cultch material, a long term decline in live oyster abundance and shell coverage can occur (Powell and Ashton-Alcox 2004). The likelihood for dredging damage to cultured oysters is greatly reduced in contemporary farming on leased beds, since oysters are spread evenly across the bottom and vertical reef structure does not form.

While extensive dredging can clearly damage established oyster reefs, other studies have shown harvest dredging to have minimal or positive effects. Manzi et al. (1985) observed little damage to oyster communities associated with mechanical harvesting. Shellfish cultivation practices can enhance oyster settlement and increase overall productivity (MacKenzie 1996). Oysters were shown to fatten quickly after feeding on fine particulates, organic detritus, and materials suspended by dredging and adjacent oyster beds showed no detrimental effects from sedimentation (Ingle 1952). Undisturbed oyster beds that become thickly covered with young oysters can experience abnormal shell growth and smothering of crowded animals. Harvesting effectively remediates this concern by breaking up crowded clumps of oysters, scattering the shells to enlarge shellfish bed, and giving the oysters more room to grow (Brooks 1905). The increased efficiency of capture associated with repeated dredging may reduce overall impacts of fishing on oyster beds. Transplantation of oysters by hydraulic suction dredge or traditional oyster dredge within Delaware Bay showed no deleterious effects on bottom complexity; cultch availability; or growth, mortality, and health of oyster populations (Powell and Ashton-Alcox 2004). Repeated dredging showed no significant impact on disease pressure, growth, mortality, or recruitment within this Delaware Bay oyster reef (Powell et al. 2001).

Increased Potential for Predation and Damage to By-catch

Shellfish and other benthic organisms dislodged but not retained by the dredge are returned to the seafloor. Nontarget infauna, attached epifauna, soft-bodied organisms, and other by-catch can be removed, damaged, or reduced through the action of mechanical harvesting (Vining 1978; Kaiser et al. 1989; Hall and Harding 1997; Auster and Langton 1999; Coen 1995; Barnette 2001; Dorsey and Pederson 1998; DeAlteris et al. 2000; NRC 2002; Morgan and Chuepagdee 2003) and can sometimes result in direct mortality (Emmett 2002). Reduction in by-catch may also result when organisms are redistributed from dredged to adjacent undredged areas (Hiddink et al. 2003). Larger motile organisms may be disturbed by dredging related turbidity, noise, and habitat disruption; removal of emergent growth; disturbance of sediments; and changes to food sources (Maier et al. 1998). Nontarget bivalves may represent 10-15 % of the harvested by-catch (Gaspar et al. 1998). Juvenile organisms which use the inshore zone as a nursery environment may also be impacted by fishing activities (Blaber et al. 2000). Effects of dredging on by-catch are determined by gear type and tow length. Composition of the by-catch can indicate the extent of disturbance experienced by benthic communities after fishing activities (Dorsey and Pederson 1998).

Scavenging and predatory organisms gain an enhanced food source when thin-shelled mollusks and annelids are damaged and left behind in dredge tracks, (Ferns et al. 2000; Wallace and Hoff 2005; Tarnowski 2006). Numbers of predators and scavenging organisms in tracks peak just after the dredge passes (Klemanowicz 1985; Hauton et al. 2003a; Morello et al. 2005). Shell breakage during harvesting operations can increase vulnerability of clams to predation (Thorarinsdóttir et al. 2008), although undamaged clams are also sometimes consumed (Meyer et al. 1981). Increased numbers of predatory flatfish and a corresponding decline in macrofaunal organisms were observed for 2 days after hydraulic clam dredging in Canada (Gilkinson et al. 2005). Predatory fish and crustaceans have been shown to increase in numbers in the vicinity of clam dredges (Manning 1960). Arrival and survival of early benthic stage fish can be compromised if fishing coincides with settlement of sessile benthic invertebrates (Langton and Auster 1999).

Many nontarget organisms survive dredge harvesting intact or sustain only minor short term effects (Maier et al. 1998). Many organisms are too small to be caught in the dredge and escape without damage (Alves et al. 2003). Very few collected mollusks and polychaetes were broken by hydraulic clam dredging in a Florida study (Godcharles 1971). Upon return to the bottom, nontarget by-catch species frequently reburrow with little harvest mortality or long term habitat alteration (Bigford 1997). Hydraulic escalator harvesting is generally less destructive to shellfish and by-catch than nonconveyer dredges since the conveyer acts to minimize damage (Tarnowski 2006). Hydraulic dredging in the offshore surfclam and ocean quahog fishery has been shown to produce a low by-catch of nontarget species (Wallace and Hoff 2005).

Most studies indicate low numbers of mobile by-catch, since active swimmers, fish and decapod crustaceans generally avoid capture (Jolley 1972; Hauton et al. 2003a, 2003b; Hawkins 2006). Shellfish harvesting gear is towed slowly for short periods of time in shallow waters, and as a result, finfish are collected infrequently (Rheault 2008). Numbers of young-of-the-year yellowtail flounder (*Limanda ferruginea)* showed no immediate decline after one time passage of a scallop dredge over an area in the New York Bight (Sullivan et al. 2003). A survey of recreational finfish in South Carolina indicated no differences in abundance related to harvesting (Maier et al. 1998). Modification of dredge design is commonly used to mitigate adverse ecological effects and to reduce by-catch of nontarget species (Gaspar and Chícharo 2007).

Clam Reburrowing After Dredging

Survival of undersized clams may be compromised by the harvest process which includes removal from the sediment, airlifting to the surface, on-deck sorting, followed by a return to the water (Robinson and Richardson 1998). Undersized clams returned to the bottom reburrow into the sediment at a rate related to their size, substrate type, and water temperature (Pfitzenmeyer and Drobeck 1967). Smaller clams reburrow more quickly than do larger clams, and reburrowing capability decreases with increasing particle size. Large adult clams (>86 mm) were shown to be least able to reburrow successfully (Rice et al.1989). Survival of sublegal clams was reduced when harvesters redeposited them in inverted positions, from which they were slow to rebury (Glude 1954).

Some clams returned to the water following dredge harvest may be unable to immediately rebury in the sediment. Razor clams returned to the bottom after dredging showed a slow initiation of “escape digging” (Robinson and Richardson 1998). Repeated mechanical stress has been shown to reduce the number of successfully reburrowing clams (*Chamelea gallina)* in the Adriatic Sea (DaRos et al. 2003). In a laboratory experiment, clams exposed to simulated harvesting disturbance experienced a reduction in burrowing speed (Marin et al. 2005).

Failure to reburrow promptly may expose shellfish to elevated predation risk (Medcof 1961; Meyer et al. 1981; Robinson and Richardson 1998; DaRos et al. 2003). Disturbed bottom attracts predatory fish and crustaceans which can feed on reburrowing or quiescent clams and other exposed benthic invertebrates (Pfitzenmeyer and Drobeck 1967). Although dredging may increase the time required for exposed clams to rebury and elevate predator abundance, it does not necessarily increase the predation rate (Chícharo et al. 2002b). An eightfold increase in predator abundance occurred just after dredging off Portugal, but mortality of clams was low, and predators dissipated quickly due to prompt reburial of exposed razor clams (Gaspar et al. 2003).

Reburial time varies with clam species. After collection by hydraulic dredging off Scotland, up to 85% of returned razor clams reburied rapidly (Hauton et al. 2003b). Undersized razor clams reburied quickly within 30 m of returning to the bottom (Hauton et al. 2003b), while small surfclams remained immobile for 1-24 h, possibly because of some form of dredge-induced shock (Meyer et al. 1981).

Dredging can loosen compacted sediments, making it easier for clams and other bivalves to reburrow successfully (Manning and Dunnington 1955). Fluidized sand offers less physical resistance to entry by the pedal muscle and shell of razor clams (Hauton et al. 2003b). The ability of clams to reburrow can be affected by the presence of vegetation, occurrence of other benthic species, water depth and currents, and predation rates as well as by substrate consistency, contour, and composition (Pfitzenmeyer and Drobeck 1967; DaRos et al. 2003). Reburial can also be impacted by environmental factors, such as temperature and dissolved oxygen levels and changes to sediment chemistry. Depletion of the oxygen layer observed after experimental dredging may present an obstacle to the reburrowing of displaced fauna (Badino et al. 2004).

Indirect Effects of Dredging Related to Habitat Disruption

Shellfish beds provide physical structure and therefore habitat for marine animals. Finfish abundance has been observed to be greater on natural oyster shell reefs than on adjacent featureless mud bottom sites (Plunket and La Peyre 2003). When dredging disrupts habitat, finfish and crustaceans may be impacted (Coen 1995). When habitat structure is altered, biomass may be reduced (Smolowitz and Nulk 1982; Coen 1995; Watling and Norse 1998; Emmett 2002; NRC 2002). Although Ingle (1952) reported that oyster dredging resulted in no damage to motile fish and crustaceans in Florida, a New Zealand study found that dredging reduced fish abundance in oyster habitat, although the population rebounded once the dredged bottom stabilized (Carbines 2005). Similarly, demersal fish in New Zealand were less abundant in one area 4 m after oyster dredging, compared to a fallow area, and this change was attributed to a reduction in habitat complexity (Carbines and Cole 2009).

Effects of Dredging on Biodiversity

Species diversity may be impacted when fishing activities remove or damage certain species and attract scavengers (DeAlteris et al. 2000; Barnette 2001). Removal of bioturbator organisms from an ecosystem by disturbance can have an indirect ecological effect on stability and maintenance of biodiversity (Widdicombe et al. 2004). Loss or alteration of habitat complexity, especially in low structure soft sediments, will reduce biodiversity (Thrush et al. 2001; Ferreira et al. 2007). In South Carolina, a diverse assemblage of species was observed in the high intertidal following dredging, while the opposite was true in the low intertidal zone (Klemanowicz 1985; Manzi et al 1985). A temporary reduction in macrobenthic diversity was associated with dredge harvesting in the waters off Portugal (Constantino et al. 2009). Diversity declined immediately following hydraulic suction dredging in Delaware Bay (Ismail 1985) while as many as 90% of species were removed by harvesting in the United Kingdom (Spencer 1997). When disturbance occurs too frequently for recovery, susceptible species are eliminated and biodiversity is reduced (Dorsey and Pederson 1998). Once hydraulic dredging has significantly reduced diversity and evenness within a biological community (Morello et al. 2006), it may take years for species diversity to return to predredging levels (May 1973). Replanting of shell and shellfish seed following dredging has the capacity to restore benthic biodiversity to its previous state. Habitats accustomed to disturbance may experience no change in diversity after dredging. In shallow, sandy, subtidal habitat near Scotland, mechanical harvesting of razor clams resulted in no apparent impact on species diversity (Tuck et al. 2000).

Shellfish culture may enhance benthic species diversity when harvested shellfish are replaced by other opportunistic organisms (Fahy and Carroll 2007). Oyster cultivation has been associated with increased species density and richer diversity (Hosack et al. 2006). Oyster beds support a greater biomass and diversity of benthic invertebrates than similar bottom without oysters (Bigford 1997). In Lousiana, species diversity on natural shell and artificial clam shell reefs was twice that observed on mud bottom (Plunket et al. 2003). Enhanced diversity in dredged areas may be due to mobilization of resources and the creation of spatial patchiness, factors which may promote recolonization by a new suite of species (DeGrave and Whitaker 1999). Small scale disturbances caused by dredging can create a spatial and temporal mosaic of successional states which can enhance community diversity (Tarnowski 2006). Dredge disturbance can prevent any one species from becoming dominant, resulting in a more diverse biological community (Collie et al. 2005). Shellfish cultivation and aquaculture promote biodiversity by increasing nutrient inputs which extend food webs (Ferreira et al. 2007). Careful selection of shellfish cultivation sites promotes biodiversity by reducing predation pressure on harvested species, increasing biological productivity, and enhancing substrate heterogeneity (Ferreira et al. 2007).

Alterations of the Biochemistry and Physiology of Shellfish after Dredging

Many experimental studies demonstrate short-term, stress-related physiological responses of bivalves to harvest processes. Hydraulic dredge harvesting can temporarily affect the physiological and biochemical metabolism of shellfish (Moschino et al. 2008). Laboratory simulations of cumulative dredging found a sublethal impact on noncommercial sized clams, *Spisula solida* (Chícharo et al. 2003). Results showed a decrease in condition as indicated by reduced biochemical indices (RNA/DNA and lipid ratios). Clams, *Chamelea gallina,* exposed to simulated mechanical sorting experienced reduced clearance and respiration rates (Moschino et al. 2008). Following simulated dredging, survival of clams exposed to air declined significantly. In field trials, high water pressure and mechanized sorting reduced scope for growth measurements, clearance rates, and survival time in air-exposed dredged clams. Shellfish exposed to actual hydraulic water jet harvesting showed a reduction in physiological well-being. Clams exposed to high pressure dredging had reduced adenylate energy charge levels and reburied less frequently than did clams in a low pressure treatment. Both of these responses are indicative of acute stress (Da Ros et al. 2003). High mechanical stress caused by dredging decreased clam filtration rates and acid phosphatase activity and increased respiration and β-glucuronidase activity (Marin et al. 2003). High water pressure reduced scope for growth measurements, increased shell damage, and affected immune response through depressed hematocrit and phagocytic index measurements. Exposure to air reduced median survival times in severely stressed clams. Observed physiological responses to high water pressure dredging suggest an acute response, although clams typically recover rapidly (Marin et al. 2003). When clams were repeatedly shaken to simulate mechanical harvesting effects (Marin et al. 2005), physiological parameters revealed a slight but statistically nonsignificant decline in their well-being, indicated by decreased filtration rates, reduced scope for growth, and increased respiration rates. When clams were stressed daily for 3 days, decreased survival out of the water and reduced burrowing speed were observed. Organisms exposed to dredging may also experience enhanced susceptibility to other stressors (NRC 2002). Physiological and biochemical effects of dredging can increase vulnerability of clams to predation, pathogens, or environmental stressors, and sensitivity to dredging may be further enhanced by factors such as season, seawater temperature, and reproductive state (Moschino et al. 2008).

Effects on Submerged Aquatic Vegetation (SAV) from Dredging

Use of dredges in seagrass habitats is currently restricted by state and federal law, but many previous studies have reported the effects of dredging on submerged aquatic vegetation. The impacts of fishing gear on seagrass systems are similar to those of plowing on terrestrial plants and vary in severity with the type of harvester (Peterson et al. 1983; Blaber et al. 2000). Lighter implements, which target shallow depths, have less impact on vegetation while heavier equipment, which sinks more deeply into sediments, is more destructive. Submerged aquatic vegetation can clog dredges, impair proper operation, and reduce catch efficiency disrupting performance (Manning 1960). Experimental studies have shown that dredging in seagrass habitat can remove, smother, or destroy SAV and algae along the dredge path (Vining 1978; Dayton et al. 1995; Barnette 2001; Morgan and Chuepagdee 2003). Hydraulic clam dredging can remove all vegetation within an eelgrass bed (Moore and Orth 1997) and prevent recolonization and diffusion (Pranovi and Giovanardi 1994). High water pressure produced by hydraulic jets can dig up aquatic vegetation, uproot plants, and suppress seed germination (Manning 1957; Godcharles 1971; Barnette 2001; Street et al. 2005; Tarnowski 2006). Plants can be defoliated, removed, or buried beneath sediment resulting in depressed growth and survival (Street et al. 2005). Other negative impacts of dredging on seagrass beds include burial of plants, disruption of root and rhizome systems, diminished plant growth, and leaf dysfunction (Jolley 1972; Tarnowski 2006). Elevated turbidity can reduce or eliminate sea grass habitat (Dayton et al. 1995). Sediments suspended by dredging can temporarily reduce ambient light and inhibit photosynthetic activity (Barnette 2001). Suction sampling can completely remove rooted vegetation from dredge tracks (Kyte et al. 1976). Trenches created by dredging in seagrass habitat may remain visible longer than in unvegetated areas (Godcharles 1971) since seagrasses create energy dampening and sediment stabilizing effects (Tarnowski 2006). Clam dredging in Chincoteague Bay, Virginia, effectively removed all vegetation in harvested areas unlike adjacent undredged bottom where vegetation remained dense and healthy (Moore and Orth 1997).

In Willapa Bay, Washington in the Pacific Northwest, oyster cultivation and dredge harvesting are successfully conducted in eelgrass habitat. Although dredging was shown to reduce eelgrass growth and biomass in oyster culture areas (Wisehart et al. 2004), higher rates of eelgrass seedling density, production, and germination have been observed after dredge harvest when compared to longline culture or hand harvest areas (Wisehart et al. 2006, 2007). In a similar study, dredged oyster beds showed lower eelgrass densities, plant size, and production than did hand picked and long line cultured beds (Tallis et al. 2006). Eelgrass density declined with increasing oyster density, likely because of competition for space or harvest damage to shoots or rhizomes (Tallis et al. 2006, 2009). Eelgrass shoots are uncommon where the seafloor is covered by oysters or shell, and bivalves can potentially damage eelgrass through breakage or wear (Tallis et al. 2009). Removal of adult eelgrass plants from the benthos allowed enhanced germination of eelgrass seedlings (Wisehart et al. 2007). Density of new eelgrass seedlings was highest in dredged oyster beds where the quantity of adult eelgrass was low. Removal of neighboring adult plants, modification of the physical environment, and the physical presence of oysters may alter the nutrient or light environment, enhancing eelgrass seed production, germination, and/or survival. Oyster dredging may promote recovery of eelgrass by liberating sources of eelgrass seed. Elevated growth rates in dredged zones may result from lower eelgrass densities, reduced intraspecific competition, or increased nutrients from oyster waste products (Tallis et al. 2006). Minimizing impacts to eelgrass is a management goal that can allow oyster culture and seagrass beds to coexist (Tallis et al. 2009).

Other types of marine vegetation can also be impacted by dredging. Macroalgal holdfast attachments may be dislodged by dredging (Vining 1978). Hydraulic harvesting of clams has been shown to reduce biomass of kelp beds (Goodwin and Shaul 1978). Damage to benthic microalgae resulting from harvest can reduce primary productivity (Auster and Langton 1999). Loss or damage to marine plants from mechanical action of the dredge can result in long term changes to co-occurring ecological communities (Pranovi and Giovanardi 1994).

It should be noted that shellfish cultivation can provide benefits to SAV. Shellfish culture can enhance seagrass productivity and/or recovery, provide an attachment site for algae, and prevent it from being transported away by currents (Brumbaugh et al. 2006; Hosack et al. 2006; Rice 2008). When feeding, oysters and other bivalves remove suspended particles from the water, increasing light at the sediment surface, and enhancing growth of SAV and benthic microalgae (Newell and Koch 2004; Newell et al. 2005; Street et al. 2005).

Evidence of Enhanced Shellfish Recruitment from Dredging

A number of studies have observed increased oyster recruitment following dredging. Enhanced settlement of oyster spat was reported after hydraulic dredge collection of softshell clams on beds in South Carolina (Burrell 1975a). Harvesting redistributes oysters from isolated clumps to expanded beds, creating more surface area for spat settlement (Kennedy and Breisch 1973). Dredging of oyster shell to collect cultch resulted in increased spat settlement on remaining shell in an Alabama study (Eckmayer 1977). Distribution of cultch on oyster beds following tong fishing was shown to increase harvests in Florida (Allen and Turner 1989). Removal of algae and silt by dredging and laying down of clean shell was shown to improve oyster recruitment in Alabama (Engle 1935). Dredge tracks may act as sinks where broken shell is trapped and retained, providing cultch for shellfish spat (Gilkinson et al. 2003). The consistent attraction of oyster spat to harvested bottom suggests that dredging does not necessarily negatively impact oyster reef development (Klemanowicz 1985; Manzi et al. 1985).

Similarly, clam recruitment has been reported to increase after beds have been dredged. Hard clams continue to settle and survive after removal of adults (Rice et al. 1989), and spreading of clean shell may contribute to increased settling densities (MacKenzie et al. 2002a, 2002b). Cultivation methods which turn over bottom sediments appear to create a more favorable environment for clam settlement (Visel 1990a, 1990b; Kyte and Chew 1975). Greater numbers of seed clams were associated with harvesting activities in Washington State (Goodwin and Shaul 1980). Recruitment of young softshell clams in Maryland increased in plots where hydraulic escalator harvesting reduced numbers of adult clams (Pfitzenmeyer 1972a, 1972b). Tilling of sediment by harvesters brings buried shell material to the surface, increases the quantity of shell hash, and significantly elevates calcium carbonate concentrations in harvested areas (Maier et al. 1998). Abundance of hard clams has been shown to increase in the presence of shell (Pratt 1953). Survivorship of juvenile hard clams in North Carolina was higher in oyster shell hash areas versus vegetated and unvegetated sand and mud/sand bottom (Peterson et al. 1995). Areas of high surfclam abundance in the Great South Bay of New York were associated with shells or shell fragments in or on the sediment surface and with the presence of relic oyster beds (Kassner et al. 1990). High shell density increased hard clam settlement in New Jersey with areas of little or no shell showing low or no recruitment (Kraeuter et al. 2003). Shell cultch may enhance clam recruitment and abundance by confusing predators, stabilizing surface sediments, or accumulating settling clams through active or passive mechanisms (Kassner et al. 1990). Shell pieces or large particles of gravel provide natural protection to small shellfish (Peterson et al. 1995), reduce current speeds to promote settlement of spat (Pratt 1953), and provide a point of attachment for the byssal threads of young clams (Wells 1957; Kraeuter et al. 2003).

Evidence of Reduced Shellfish Recruitment or No Observed Effects from Dredging

Some evidence suggests that cultivation may have a negative effect on settlement or may not result in enhanced recruitment. Dredging may disrupt or partially bury oyster spawning stock, removing potential settling surfaces and decreasing numbers of oyster spat (Drobeck and Johnston 1982; Kaiser et al. 1989; Breitburg et al. 2000). At one time, oyster harvesting was so intensive that few oysters and little shell remained to provide cultch material for ready-to-settle oysters (MacKenzie 2007), reducing recruitment potential. Removal of shell can reduce buffering capacity and lower pH, causing shell dissolution and mortality of juvenile shellfish (Green et al. 2009). Total oyster spatfall on a harvested reef was lower than that found in a nearby control area in South Carolina (Manzi et al. 1985). Other bivalve species have also demonstrated a decline in recruitment following shellfish harvest. Suction dredging for cockles reduced settlement substrate for the blue mussel (*Mytilus edulis*) (Hiddink et al. 2003) and had long lasting negative effects on recruitment of bivalves in sandy areas (Piersma et al. 2001). Disturbance from dredging and subsequent loss of fine grained sediment may account for declines in shellfish recruitment.

Dredge harvesting may have no impact on shellfish recruitment. No increase in hard clam recruitment was observed following escalator dredge harvesting in either Florida (Godcharles 1971) or Virginia (Haven 1979). Softshell clam spat was equally abundant in hydraulically harvested areas and unharvested locations in South Carolina (Burrell 1975b). Plots dredged on a daily or weekly basis showed similar recruitment of soft-shell clams in Maryland (Pfitzenmeyer 1972a, 1972b). Artificial shelling of bottom in the Great South Bay of New York showed no increase in surfclam recruitment one year later, despite observations of elevated clam abundance in adjacent areas with high natural shell (Kassner et al. 1990).

Chemical Effects of Dredging

The chemistry of bottom sediments may be altered when the benthos are disturbed by dredge activity. Modification of the benthic community as a result of dredging can impact the exchange of chemicals and nutrients between the sediments and water column and affect system dynamics. Cultivation of bivalve shellfish can also improve water quality and redistribute chemical constituents within sediments. Dredging may modify the biogeochemistry of sediments to favor settlement and recruitment of shellfish. In the following section we report the effects of shellfish dredging on sediment chemistry as described in the literature. Although many experimental studies have directly addressed the physical and biological effects of dredging, information on chemical effects is more limited and derived from the basic understanding of benthic processes.

Sediment Biogeochemistry

The biochemistry of marine sediments is largely influenced by bioturbation and burrowing activities of benthic organisms. The mechanisms by which benthic invertebrates obtain food produce the chemical transformations that regulate carbon, nitrogen, and sulfur cycling; water column processes; distribution and fate of pollutants; secondary production; and transport and stability of sediments (Dame, 1996; Snelgrove 1997; Widdicombe et al. 2004). This interaction is particularly true for deposit feeders which dominate depositional areas of silt/clay fine sediments that result from limited water movements (Wildish and Kristmanson 1997). Bottom dwelling organisms stabilize sediments through tube construction and mucous binding of particles and contribute to sediment destabilization via bioturbation processes (Snelgrove 1997). Since benthic organisms involved in sequestering and recycling processes are essential to ecosystem function (Thrush and Dayton 2002) their removal or disruption by dredging can alter sediment biogeochemistry. Removal of large benthic bioturbators through dredging can have long term effects on sediment nutrient fluxes and influence whether the seafloor acts as a source or sink for nutrients (Olsgard et al. 2008).

Dredging disturbance can alter the biogeochemical composition of sediments. Physical changes in sediment compaction from dredging can alter the magnitude and rate of biogeochemical cycling between the sediment and overlying water (Badino et al. 2004). Disruption of the substrate by harvesting can change the rate of resuspension and enhance the upward flux of nutrients in pore water from periodic release to pulse (Auster and Langton 1999; Thrush and Dayton 2002). In one study conducted in Portugal, ammonium, nitrates, organic nitrogen, phosphates, and silicates decreased in porewater of reworked sediment immediately after dredging with a simultaneous increase in nutrient levels in near bottom water, but these chemical characteristics returned to previous levels within hours (Falcão et al. 2003). Chemistry of sediments within dredge furrows may differ from that measured along the outside ridges where substrate material was reworked by harvesting (Falcão et al. 2003). In Washington State, removal of substrate material by dredging caused little or no reduction in chemical parameters such as biological oxygen demand, nitrogen, sulfides, and phosphates within harvested areas (Goodwin and Shaul 1978). Experimental hydraulic dredging in Narragansett Bay had no measurable impact on total organic carbon of sediments (Sparsis et al. 1993). In many cases, chemical impacts of seabed disturbance are both localized and temporary in nature (DeAlteris et al. 2000).

Dredging can enhance system metabolism, impact water column processes, and influence trophic transfer. Suspension feeding bivalves serve an important chemical role in coastal ecosystems by transferring nitrogen and phosphorus from the water column to the sediments (Newell 1988; Newell and Koch 2004; Newell et al. 2005). Bivalves ingest and process resuspended organic matter, which is returned to the environment as biodeposits (feces and pseudofeces) (Snelgrove 1997; Pranovi et al. 2003). Biodeposition, accumulation, and remineralization of organic matter from these shellfish waste products affect the biogeochemical properties of sediments which drive biological community structure (Dame 1996; Cranford et al. 2006). Increased availability of nutrients modifies the lower food chain by reducing microbial activity (Morgan and Chuepagdee 2003) or increasing the role of smaller organisms and bacteria (Dorsey and Pederson 1998). The metabolic activities of bivalves can accelerate the movement of carbon, nitrogen, and phosphorus between sediments and the water column (Dame 1996).

Benthic macrofauna regulate chemical cycles, irrigate and mix the sediment, redistribute oxygen, and enhance pore water exchange with the overlying water column (Pranovi et al. 2003).

Organisms that construct multidimensional burrows and tubes provide conduits for pulling oxygenated water into the sediments, and some organisms, which oxygenate sediments to even greater depths, occur in deeper anoxic sediment (Watling 2005). Shellfish cultivation activities may promote short-term redistribution and increased oxygen and minerals within bottom sediments. Substrate overturned by dredging can enhance oxygen penetration into the upper sediment layers (Falcão et al. 2003). Organic carbon in the first inch (25.4 mm) of undisturbed sediment may be redistributed within substrates by dredging (Pfitzenmeyer 1972a).

Disruption of surface sediments by dredging, however, can sometimes create short term and localized oxygen deficits in the water column (Bartoli et al. 2001), decreasing dissolved oxygen concentrations. Resuspension of sediments and subsequent release of previously buried organic material into the water column may create an oxygen deficit (Aspden et al. 2004). When dissolved oxygen is reduced by disturbance of the seafloor environment, the risk of hypoxia affecting the associated biological community is elevated (NRC 2002; Rheault 2008). Stress from dredging can increase biological oxygen demand among benthic organisms (Coen 1995). Depletion of the oxidized layer can inhibit reburrowing of infauna displaced during harvesting operations and reduce faunal activity postharvest (Badino et al. 2004). Stimulation of oxygen and carbon dioxide fluxes by clam culture can affect nutrient regeneration rates across the water-sediment interface (Bartoli et al. 2001). Low dissolved oxygen and slightly reduced pH values associated with dredging indicated that reduced sediments were resuspended by dredging and mixed back into the water column (Kyte et al. 1976). The associated decline in oxygen and pH appeared short term, as sediments oxidized rapidly. Tilling of sediments brings buried shell and shell hash to the surface and can increase calcium carbonate concentrations in harvested areas (Maier et al. 1998). There is evidence that recruitment among sediment dwelling bivalves can be enhanced by distributing shell hash to increase pore water calcium carbonate saturation levels (Green et al. 2009) and pH concentrations, a practice commonly used by shellfish farmers to boost clam recruitment. In some cases, however, removal of extensive quantities of old shell during harvest may lower sediment pH, potentially impacting larval settlement (Green et al. 2009).

When large shellfish are dredge harvested, minerals and nutrients are removed from the ecosystem (NRC 2002; Cranford et al. 2006). Shellfish cultivation and production sequesters nitrogen in the form of protein in meat and shell and stabilizes phytoplankton growth dynamics through modulation of ammonia cycling in the water column (Rice 2008). With each harvested oyster (7.6 cm length), 0.52 g nitrogen and 0.16 g of phosphorus are eliminated from the marine environment (Newell and Koch 2004; Rheault 2006). Actively growing shellfish can remove as much as 16.8 g of nitrogen from an estuary for every kg of meat harvested (Rice 2001). Dredging may also act to liberate nutrients, metals, or contaminants from anaerobic bottom sediments (Coen 1995; Watling and Norse 1998; Barnette 2001; Northeast Region EFHSC 2002). Although bivalves can tolerate high concentrations of pollutants such as heavy metals (Stiles et al. 1991), release of significant quantities of toxicants seems unlikely since harvestable bivalves are presumably associated with cleaner substrates (Kennedy and Breisch 1973). The likelihood of pollutant impact is relatively minor since bivalve shellfish occur in moderate to high energy environments where substantial current velocity provides constant flushing and good circulation, contributing to high water quality (Vining 1978).

Socioeconomic Effects of Dredging

Small scale shellfish harvesting can provide benefits to coastal community shareholders. In Connecticut, oyster farming produces 300 jobs, $15 million in revenue, and an annual oyster harvest of 450,000 bushels with operations conducted within a small area relative to the broader Long Island Sound ecosystem (Connecticut Department of Agriculture 2011). Cultivation can expand the marine economy through promotion of private investment, creation of shellfish farms and jobs, reestablishment of traditional shellfish aquaculture, generation of income for state and local governments via the licensing and leasing process, initiation of employment opportunities for coastal communities, development of shoreline processing facilities, and finally, production of high-quality locally-farmed shellfish for consumer markets and restaurants (Vining 1978; Ferreira et al. 2007; Cashin Associates 2008a, 2008b). Contemporary cultivation methods enhance spawning potential of native shellfish, improve utilization of growing areas; reduce harvesting labor; increase landings; and allow more efficient movement of shellfish to depuration areas, better access to underwater land for raising shellfish, effective transportation of seed and increased economic gain for shellfish growers (Vining 1978; Manzi et al. 1985; Cashin Associates 2008a, 2008b). Superior water quality and stewardship of marine resources are associated with active shellfish culture and result in a positive relationship between ecological health and users of the coastal zone (Cashin Associates 2008a, 2008b). Shellfish aquaculture can meet objectives for environmental and social sustainability, help meet the world's needs for aquatic foods, and contribute to food security, and economic development (World Wildlife Fund 2009).

Dredging may also impact coastal communities. Harvesting can disrupt marine recreational activities, create hazards to navigation, detract from the visual aesthetic, increase onshore noise levels, and result in a loss of some maritime traditions (Vining 1978; Barnes et al. 1991; Rice 2008; Cashin Associates 2008b). Shellfish cultivation on leased beds could potentially result in inadvertent harvesting activity on unauthorized bottom impacting private property owners (Vining 1978). Actions such as muffling sound from vessels, restricting working hours, and marking leased bottom to prevent infringement on unleased areas all provide possible solutions to these issues. The short term nature and limited spatial scale of most shellfish dredging on leased grounds could largely mitigate many concerns. Harvesting a resource that would otherwise be lost to natural perturbations may outweigh potential short term effects (Kaiser et al. 1998).

Duration of Dredging Effects

In many studies, the impacts of shellfish dredging on aquatic resources, benthic food webs, or marine ecosystems were of short term duration (Stokes et al. 1968; Vining 1978; Kaiser et al. 1996; Marsh 2004). Hydraulic dredging over a 30 y period in the Adriatic Sea showed no lasting effect on benthic fauna such as polychaetes, crustaceans, detritus, and suspension feeders (Morello et al. 2005). Hydraulic escalator harvesting of softshell clams in Maine showed few significant changes in biological, geological, and hydrographic systems at the harvest site (Kyte et al. 1976). In South Carolina, escalator harvesting caused no long-term chronic impacts, and effects were indistinguishable from ambient levels of natural variability (Coen 1995). Studies in Maryland and South Carolina showed minimal and temporary impacts of dredging on bottom dwelling invertebrates, finfish, and infaunal benthic communities (Drobeck and Johnston 1982; Maier et al.1998).

Studies have shown that, in many cases, clam dredging has no long term negative impact on the benthic community. Hydraulic dredging for surfclams had no harmful effects on resident benthic organisms on either a long or short term basis (Lambert and Goudreau 1996). In Narragansett Bay, one time disturbance of sediment by a hydraulic bullrake during clam cultivation resulted in no significant differences among infaunal communities when compared with an untreated control. Further, the scale of observed seafloor effects was much lower than the observed natural spatial and seasonal variability (Sparsis et al. 1993). Experimental short raking of quahogs from sand sediments in Raritan Bay, New Jersey had no measurable effects on the number of benthic invertebrates (MacKenzie and Pikanowski 2004). Clam (quahog) harvesting in North Carolina had no effect on density or species composition of small benthic macroinvertebrates; these findings were attributed to their rapid recolonization and short life spans (Peterson et al. 1987). Suction dredging for Manila clams in England left no long term effect on the environment or benthic community (Kaiser et al. 1996). Effects of dredging on softshell clam abundance in Maryland were largely considered to be short term (Pfitzenmeyer 1972a, 1972b), since heavy annual sets, rapid growth rates, and the ability to reburrow fostered rapid recovery rates among populations (Pfitzenmeyer 1972b; Drobeck and Johnston 1982). Communities thriving in hydrodynamic areas, well-adapted to natural physical stress, do not appear greatly affected by clam dredging (Constantino et al. 2009).

Mechanical harvest of oysters has also been shown to have minor effects on the benthos. Sampling conducted prior to and just after hydraulic escalator oyster harvesting in South Carolina showed no negative effects on benthic organisms (Burrell 1975a). Mechanical harvesting in South Carolina caused little or no damage to oysters (Collier and McLaughlin 1984). At present levels of exploitation, oyster dredging in Delaware Bay is thought to have a benign impact on the health and productivity of oyster populations (Powell et al. 2001).

Practices associated with shellfish harvesting do not appear to inhibit shellfish reproduction, interfere with replacement of harvested stocks (Manning 1960), or consistently impair shellfish recruitment processes (Tarnowski 2006). Detrimental effects of fishing disturbance are generally short term because shellfish and other organisms removed by dredging are replaced through natural recruitment processes (Bigford 1997) or by replanting of shell and seed as part of the cultivation process. Dredging does not collect every marketable clam, so those that remain serve as broodstock and can repopulate harvested areas (Manning and Dunnington 1955) through the seasonal arrival of new recruits (Gilkinson et al. 2003).

ECOLOGICAL RECOVERY AFTER DREDGING

Experimental studies, conducted at differing spatial scales, show that reestablishment of benthic communities and recovery of infaunal abundance, taxonomic richness and biomass following dredging occurs within a matter of hours, days, weeks (Godcharles 1971; Hall et al. 1990; Hall and Harding 1997; Ferns et al. 2000), or months (Ismail 1985; Kaiser et al. 1996; Spencer 1997) with recovery often complete within one year (Simon and Connor 1977; Connor and Simon 1979). The hydrodynamic energy within an environment determines recovery rate which can range from days in high energy areas to months in low energy habitats (Wallace and Hoff 2005). On intertidal flats the ecological recovery rate among benthic communities varies but generally is rapid following hydraulic clam harvest (Goodwin and Shaul 1980) or suction dredging (Spencer et al. 1998). Tarnowski (2006) provides a table summarizing recovery times for coastal and estuarine benthic fauna exposed to different kinds of disturbance, including shellfish dredging. He reports that benthic equilibrium following disturbance generally returns within a 12 m period. Biomass in particular can be slow to recover since it responds to growth rates of newly settled organisms and immigration into the area (Tarnowski 2006). Recovery from dredging reflects the ability of damaged organisms to repair, regenerate, and withstand conditions within disturbed habitat, as does successful larval production, settlement and recruitment to the adult population (MacDonald et al. 1996). Recovery times vary with the intensity, frequency and spatial scale of disturbance, the physical characteristics of the habitat, and the life history attributes of resident species (Northeast Region EFHSC 2002).

Recolonization after dredging is an ongoing process, dependent on natural recruitment. For example, in Canada, abundance of polychaetes and amphipods continued to increase for over a year after harvesting (Gilkinson et al. 2005). Organisms within the same community may recover at differing rates based on their individual level of sensitivity to disturbance (Beukema 1995). A meta-analysis of general effects from different types of fishing gear found the most rapid recovery in less physically stable habitats where opportunistic species occur (Collie et al. 2000). Recovery occurs most quickly in less-consolidated sediments where resident organisms are adapted to disturbance by anatomy, behavior, or life history characteristics (Dorsey and Pederson 1998; NRC 2002). Areas prone to frequent disruption select for species which tolerate instability and favor communities dominated by juvenile stages, mobile species, and rapid colonists (Dayton et al. 1995; Thrush and Dayton 2002). For resident organisms to survive, they must adapt to the dredged environment while new colonizers may be attracted to altered seafloor (Kyte and Chew 1975). Most species living in frequently disturbed areas have evolved characteristics that allow them to reside or repopulate these areas (Watling 2005). Rapid recovery following clam cultivation in Narragansett Bay, Rhode Island was attributed to the short life spans of the dominant organisms, amphipods, and polychaetes (Sparsis et al. 1993). Settling of lighter organisms following the resettlement of suspended sediment might account for the minimal damage to infauna observed. Despite the creation of 1 m deep grooves during this experimental study of hydraulic dredging effects, recovery of the sediments and biota was almost immediate. Effects of shellfish harvesting are short term where the infaunal benthic community expresses an opportunistic recolonization response (Drobeck and Johnston 1982).

The type and spatial extent of habitat can influence initial mortality rate, benthic community recovery and species composition following disturbance (Adkins et al. 1983; Link et al. 2005). Shellfish cultivation is conducted in environments coinhabited by short-lived, disturbance-tolerant, opportunistic organisms (NRC 2002) which appear less affected by fishing activities than are stable deepwater communities (Auster and Langton 1999; Barnette 2001). Species residing in coastal waters and accustomed to rapidly changing habitats and environmental conditions are resilient and recover quickly from disturbance events (Taranowski 2006). Rigorous and dynamic estuarine environments, characterized by large predictable and unpredictable fluctuations in environmental variables, are subject to almost constant disturbance (Turner et al. 1995). Effects of dredging appear low and benthic community recovery rapid in shallow hydrodynamic environments (Constantino et al. 2009). This observation is in contrast to stable biogenic gravel and mud seabeds, inhabited by long-lived benthic organisms, which experience a greater loss of flora and fauna and recover more slowly after disturbance than do sandy sediment communities (Dorsey and Pederson 1998; Auster and Langton 1999).

The nature, magnitude, and frequency of impact, recovery time of the habitat, and scale of cultivation determine the duration of harvest impact (Kaiser et al. 1998; Johnson 2002). Recolonization rate and restoration of sediment structure vary with local hydrology, wave action, currents, sediment stability, natural disturbance, recruitment rates, and presence of SAV

(Godcharles 1971; Adkins et al. 1983; Spencer et al.1998). The ability of a habitat to recover from fishing disturbance is often a function of wind, wave, and tidal action (Stevenson et al. 2004). Infaunal communities recover faster than do emergent epifauna (Northeast Region EFHSC 2002), and recovery rate of benthic fauna is faster at shallow water depths (Constantino et al. 2009). Use of the same dredge in several areas can result in different recovery and recolonization patterns depending on previous exposure of the seafloor to disturbance (Pranovi et al. 1998). Recovery can be quicker in previously dredged versus newly dredged areas because of greater adaptation to stress by organisms already present in the disturbed site (Pranovi and Giovanardi 1994).The recovery rate of habitat depends on whether disturbance is a one time instance or persistent multiple events with cumulative effects (Northeast Region EFHSC 2002; Wilber et al. 2008). Frequent dredging of sheltered areas may have a significant impact on biological recruitment, productivity, and benthic community structure (Hauton and Paterson 2003). Repetitive disturbance may impede sediment consolidation, disrupt succession of biological communities, prevent establishment of stable benthic assemblages (Aspden et al. 2004), and may interfere with recruitment processes (Watling and Norse 1998). The interval between disturbances is critical for the ability of benthic organisms to repopulate because time between events can be short relative to the life span of certain species (Watling and Norse 1998; Watling 2005).

Ecosystems respond to disturbance with changes to species composition, abundance, or biomass (Dorsey and Pederson 1998). Invertebrates undergo a natural pattern of community development after dredging (Klemanowicz 1985). In some cases, organisms rely on disturbance to create conditions favorable for recruitment, growth, and reproduction (Sousa 1984; Dernie et al. 2003a, 2003b). Physical changes to topography, sediment, or removal of organisms can alter ecological community structure and modify the environment so it is more or less suitable for the existing community (Langton and Auster 1999; Tarnowski 2006). This promotes establishment of an alternative bottom community with different species composition, functions, and ability to provide ecological services (Zajac et al. 1998). Where fishing is frequent, few long term effects are observed because the resident biological population has been selected for adaptation to disturbance (Watling and Norse 1998). Communities can return to their previous state when disturbance is not too intense, the time interval between disturbances is sufficient, the system has high resilience, and/or harvesting is discontinued (NRC 2002). Benthic community structure may not completely return to its previous state until bottom substrate stabilizes (Goodwin and Shaul 1980). Resilient communities can maintain structure and function even in the presence of frequent disturbance (Zajac et al. 1998).

Chronic disturbance from fishing activity may prevent benthic succession from proceeding to climax communities (Watling and Norse 1998). Reduction or replacement of organisms caused by mobile gear may prevent an ecosystem from returning to its original state, even in the absence of fishing (Northeast Region EFHSC 2002). There may be a threshold of intensity or a cumulative effect beyond which persistent changes to the ecosystem occur (NRC 2002) or a level of anthropogenic impact beyond which even populations resistant to disturbance collapse (Pranovi et al. 1998). Marine communities are threatened when fishing-related changes occur faster than nature can respond (Thrush and Dayton 2002). If disturbance exceeds recovery time, susceptible species will be eliminated and biodiversity reduced (Dorsey and Pederson 1998). It is not known whether benthic communities with a prolonged history of disturbance will return to their original state after disturbance ends or if the ecosystem would now be too altered to recover (Zajac et al. 1998). In areas subject to repeated-dredging disturbance, a return to preharvest ecological conditions may be an unrealistic expectation (Wilber et al. 2008). Some studies which followed dredged areas for an extended period detected no or incomplete recovery of benthic communities (Gilkinson et al. 2003, 2005). Studies of fishing disturbance are often short term, and the period required for complete recovery may exceed the duration of experimental monitoring (Tarnowski 2006). Longer term studies might allow a better understanding of natural cycles of postharvest recovery and recruitment within the context of larger ecosystem level influences including global warming, ocean acidification, and other anthropogenic factors (Gaspar and Chícharo 2007).

Seasonal Changes Affect Recovery from Dredging

Recovery from dredging occurs against a background of natural seasonal changes (Hall and Harding 1997) and benthic recovery rate is impacted by the time of year when harvesting occurs (Pfitzenmeyer 1972a, 1972b; Langton and Auster 1999). Recovery happens quickly when seasonal dredging avoids sensitive periods of larval recruitment (Ismail 1985). Repopulation is mitigated through active migration and passive transport processes, and recovery is closely tied to the reproductive cycle of constituent species (Hall et al. 1990; Tarnowski 2006). Immigration-based recovery begins just after the disturbance ends, while recruitment may have a strong seasonal or annual signal corresponding to reproductive cycles (Langton and Auster 1999). Numbers of commercial-sized, softshell clams in dredged and undredged areas of Maryland returned to similar levels 4 m after spring harvest but differed for up to a year following late summer dredging because of seasonal differences in recovery (Pfitzenmeyer 1972a, 1972b). The time frame necessary for restoration is influenced by timing of harvest with regard to recruitment of both target and nontarget organisms (Kaiser et al. 1989; Spencer et al. 1998).

Marine ecosystems are subject to many weather-related seasonal changes (e.g., storms, salinity fluctuations, and icing) which can make it difficult to distinguish harvesting effects from disturbances caused by natural events. Impacts of mobile fishing gear can mimic benthic changes caused by natural disturbance (Street et al. 2005). In many cases, changes to the seafloor induced by wind, waves, currents, tide, and storms may exceed those caused by shellfish harvesting (Drobeck and Johnston 1982; Bigford 1997; Alves et al. 2003; Rheault 2008; Constantino et al. 2009). Infrequent and low intensity harvesting have impacts within the range of naturally occurring habitat perturbations (Barnette 2001). Experimental studies have shown that faunal changes are sometimes more strongly linked to natural seasonal variability than to dredging effects (Godcharles 1971). In a study of hydraulic harvesting of hard clams in Narragansett Bay, natural spatial and seasonal variability exceeded the effects of bottom cultivation (Sparsis et al. 1993). This finding suggests that shellfish dredging may represent a small-scale and short-term impact relative to other natural environmental processes (Alves et al. 2003).

The relative significance of dredging disturbance should be evaluated in the context of how magnitude and frequency of natural disturbance impacts the dredged environment (DeAlteris et al. 1999; Constantino et al. 2009). Effects of mechanical shellfish harvesting must be detectable above natural and temporal variability in dynamic study areas (Gilkinson et al. 2003; Morello et al. 2006). Large spatial effects of mobile fishing gear can be masked by co-occurring natural disturbances, while effects from small scale disturbances may not be apparent where recolonization occurs rapidly (Kaiser et al. 1998). Knowledge of seasonal, annual, and spatial variations in benthic assemblages should be considered when assessing the impacts of disturbance caused by mobile fishing gear (Løkkeborg 2005).

MITIGATING EFFECTS OF SHELLFISH DREDGING

The practice of sustainable shellfish cultivation means avoiding, remediating, or mitigating any adverse effects of harvesting on the aquatic environment (Beentjes and Baird 2004). The minimal, short-lived, and localized nature of shellfish harvesting practices can be further reduced through responsible program modifications (Barnes et al. 1991). Long term disruption of the seafloor environment by dredging can be controlled through a combination of selective harvesting practices, careful site selection, rotational seeding, cultivation, creation of fallow areas, and seasonal harvesting to avoid disrupting larval shellfish recruitment and to allow time for recovery (Kaiser et al. 1989; Spencer et al. 1998). Management of renewable shellfish resources includes habitat preservation and limiting harvest to surplus populations (Hargis and Haven 1999). Effective management of shellfish populations includes creation of habitat for a variety of marine species, water and sediment quality enhancement, stabilization of critical shoreline habitat, and maximizing harvested product (Opton-Himmel and Whelchel 2010). Restoration of shell material to dredged bottoms following harvest could mitigate any negative effects associated with cultivation by providing fresh cultch for settling larvae (Manzi et al. 1985). Creation of unharvested refuge areas can protect populations of broodstock oysters to help ensure adequate larval supply and recruitment (Breitburg et al. 2000). Regulatory restrictions can prevent harvesting during periods of peak biological activity or reproduction and can create broodstock and seagrass sanctuaries (Tarnowski 2006). Potential adverse effects of dredging on essential fish habitat can be mitigated by fishing equipment restrictions, area closures, and harvest limits (Wallace and Hoff 2005). Modifications to harvesting equipment can reduce certain impacts but may require trade-offs. While trials of a new hydraulic clam dredge with vibrating bottom grid improved size selectivity, allowed escape of undersized clams, reduced nontarget by-catch, and enhanced the quality of commercial catch, this dredge also increased slightly the number of shells damaged during harvesting (Rambaldi et al. 2001).

Ecological effects of hydraulic escalator dredging are often mitigated by the attributes of the target species and the physical dynamics of inshore coastal ecosystems where harvesting occurs. In most cases, hard-shelled bivalve species show high resilience to and recovery from harvesting impacts. Benthic communities established in response to historical shellfishing practices demonstrate rapid recovery to disruption (Tarnowski 2006). Since high-energy environments with resilient biological communities recover quickly from disturbance, the physical and biological attributes inherent to these ecosystems help offset the effects of dredging and may account for the rapid elimination of morphological and sedimentary impacts of harvest (Constantino et al. 2009).

Shellfish cultivation may improve habitat quality. Some natural shellfish beds lack the physical or biological factors necessary for successful growth, and this condition can limit shellfish abundance (MacKenzie 1989). Hydraulic shellfish harvesters have been used as a remediation tool to treat marginal clam habitat and enhance the substrate for improved survival of transplanted clams (Nickerson and Brown 1979). Cultivation of oysters can prevent the mortality or malformation that occurs in natural undredged oyster beds, when animals growing side by side in clusters become too crowded for normal healthy growth (Brooks 1905). Hydraulic dredging can decrease the quantity of anoxic sediments and enhance shellfish production (Visel 2008). Increased clam abundance is associated with relocation of shellfish to cleaner areas for depuration, periodic cleaning of cultch to remove silt, cultivation of bottom sediments, and addition of shell to reduce acidity (Visel 2008). Periodic resuspension of fine sediments and organics by dredging can improve sediment quality (Emmett 2002). Hydraulic harvesting removes old shell cover from the bottom, loosening sediment, and improving grain size (MacKenzie 1979). Shellfish cultivation may increase pore area within sediments, improve circulation, and elevate pH levels which can positively impact clam populations (Visel 1990a). Dredging stirs up organic detritus which may enhance shellfish production by increasing food availability for filter feeding organisms (Pranovi et al. 2003). Release of nutrients from sediments into the water column can create a food source, and temporary turbidity can create a predation refuge for benthic fish and invertebrates (Dorsey and Pederson 1998; Auster and Langton 1999).

AREAS FOR FURTHER RESEARCH AND CONCLUSIONS

Understanding all potential effects of shellfish dredging on physical habitat, biological communities, and biogeochemistry of sediments is challenging. Designing a statistically defensible experimental study that comprehensively evaluates harvesting effects requires direct comparison of dredged areas to undredged areas in close proximity that have similar habitat, environmental, and hydrodynamic characteristics. Sampling treatment areas prior to experimental dredging may help account for seasonal effects. In an ideal study, effects of dredging in different seasons would be compared at different durations and intensities and over a wide range of spatial scales. Optimally, physical changes to the bottom would be documented by using photography, video, or sonar. Impacts to the biological community would be determined through intensive sampling of benthic infauna and epifauna. Analyses of sediment at different depth strata would be used to determine the magnitude and duration of biogeochemical changes. Data that define habitat, sediment type, and grain size would be important, as well as a detailed description of the dredge gear, including its dimensions and degree of impact. Further, spatially extensive, long-term monitoring would be valuable to give an ecosystem-level context to the study. Unfortunately, many of the research studies we report in this document lack key elements in their experimental design or methods. Differences in spatial scale, geography, dredging equipment, habitat and sediment type, and experimental design make it difficult to directly compare results across studies and draw universal conclusions concerning dredging impacts.

Despite an abundance of literature concerning shellfish dredging, there are no definitive “one size fits all” answers to questions concerning the impact of shellfish harvesting. From experimental studies, it is clear that the observed physical, biological, and chemical effects of dredging are highly variable. The level of impact resulting from shellfish dredging corresponds to the spatial and temporal scale, sediment type, harvesting equipment, biological community, environmental attributes of the ecosystem, and the assessment metrics used to evaluate effects over time. Physical alteration of the seafloor resulting from dredging usually reverts back to its prior state through the natural physical processes of tides, currents, and storms. Ecological recovery of benthic biota following dredging is linked to natural and ongoing seasonal recruitment processes. In dynamic, shallow-water, coastal areas that regularly experience natural disturbance and where the duration and spatial scale of dredging is limited, ecological recovery is usually rapid. Common, fast-growing benthic organisms with short generation times quickly recolonize benthic habitats following dredge disturbance. Bioturbation and other natural processes can restore sediment biogeochemistry. When considered in this context, the impacts of shellfish dredging are minor relative to the many natural disturbances that occur within the coastal marine environment. The effects of dredging in shellfish cultivation are further mitigated by its generally limited spatial and temporal scale and the use of sound harvesting practices on leased grounds.

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Table 1a. Dredging effects reported from research studies on the northern quahog, *Mercenaria mercenaria*. N/A indicates no data.

Habitat Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Recovery	Author
Tidal river bottom	Hydraulic escalator dredge	Santee River, South Carolina	No harmful effects on biota, more live oysters found after harvest because of early spat settlement, fewer found where harvesters removed commercial sized animals	N/A	N/A	N/A	Burrell 1975a
Subtidal mixed sediment	Hydraulic escalator dredge	Santee River, South Carolina	Amount of spat in water column similar between harvested and unharvested areas	0.1 M tow depth	N/A	N/A	Burrell 1975b
Firm sandy mud	8 and 12-toothed clam dredges	Narragansett Bay, Rhode Island	1% gear-related breakage of commercial sized clams, low breakage or smothering of undersized clams, removed clams > 60 mm, decreased tube worms	Mixing of sandy-mud and clay layer more pronounced than in control area, sediment was also softer	N/A	N/A	Glude and Landers 1953
Mud and sand	Hydraulic escalator dredge	Rappahannock, James and York rivers, Virginia	Dredging did not increase hard or soft clam set, oysters 75-100 ft from dredged area were unaffected, dredging uprooted eelgrass and removed invertebrate tubes	Dredging changed appearance, composition and texture of seafloor, created trenches 6-8 inches deep, reduced silt-clay fraction, moved buried shell to surface, effects within 75 ft of dredge	N/A	Trenches refilled within 1-2 months	Haven 1979
Assorted sediments sand, silt, clay, $CaCO_3$,	Hydraulic escalator harvester	South Carolina Tidal creeks: Back Creek, Hamlin Creek, Summerhouse Creek, 2 creeks near Isle of Palms	After harvest polychaetes decreased, amphipods increased, diversity and abundance increased, no difference in mobile fish and invertebrates	Elevated turbidity in vicinity of harvest, plumes extended < 2 km, highest < 1 km away, several hours duration, increased $CaCO_3$ and decreased clay following harvest	N/A	N/A	Maier et al. 1998

Table 1a, continued. Dredging effects reported from research studies on the hard clam, *Mercenaria mercenaria*. N/A indicates no data.

SAV beds	Clam dredge	Chincoteague Bay, Virginia	SAV absent from dredge circles, vegetation was dense and healthy just outside of dredge zone	Dredging disrupted sediments from rich organic sand to coarse sand and broken shell	N/A	Predicted that recovery of SAV will exceed 5 yrs	Moore and Orth 1997
SAV beds	Clam dredge	Chincoteague Bay, Virginia	15% less vegetation than found at scar edge, low cover in scar area except at center	Increased bottom depth in scars, large holes up to 1 meter diameter and 30-40 cm deep	N/A	Rate of revegetation related to scar size, dredging intensity, and remaining vegetation; topography and sediment type may hinder rate of revegetation	Orth et al. 1998
Seagrass bed and sand flat	Clam "kicking" and raking	Back Sound, North Carolina	Raking and light clam kicking: seagrass declined 25% below controls; intense clam kicking: 65% decline, clam harvest had no effect on density or species composition, harvest did not boost clam recruitment	N/A	N/A	Raking/ light clam kicking: SAV recovery in 1yr, intense kicking: recovery in 2yrs, SAV remained 35% lower than control after 4-yrs	Peterson et al. 1987

Table 1b. Dredging effects reported from research studies on the softshell clam, *Mya arenaria*. N/A indicates no data.

Habitat-Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Recovery	Author
Intertidal flats	Hydraulic escalator dredge	Nova Scotia, Canada	Removed 90% of small clams and 50% of market sized, 1% shell breakage	Dug to 14 in depth, high efficiency	N/A	N/A	Dickie and MacPhail 1957
Mud and sand substrate	Hydraulic escalator dredge	Chesapeake Bay, Virginia	Dredging did not increase hard or soft-shell clam set, oysters 75-100 ft from dredged area unaffected	Seafloor appearance, composition, and texture altered; removed invertebrate tubes; trenches 6-8 in. deep, reduced silt-clay fraction; moved buried shell to surface; changes occurred within 75 ft of dredge	N/A	Trenches filled within 1-2 months	Haven 1979
Silt-clay intertidal flats	Hydraulic escalator dredge	Harraseeket River, Maine	Few significant changes: *Corophium volutator* declined, vegetation uprooted in tracks, clams intact and unbroken, decrease in large clams, decline in polychaetes, increase in *Macoma balthica*	Solid clay removed from flats creating a trench filled with soft sediments, turbidity briefly increased as a plume but suspended solids returned to low levels, created trenches 30-45 cm deep and mounds of spoils	Slight changes in chemical parameters, low DO and pH indicate reduced sediment brought up by dredge into water column, was quickly oxidized	Trenches hard and well defined for 2 months, spoil heaps lasted 2-3 months, at 10 months trenches had fine, soft sediment 5-8 cm below normal flat, major species increased by 10 months	Kyte et al. 1976
Muddy soil, sandy further toward beach	Hydraulic clam rake	Pottery Bridge Flat, St. Andrews, Canada	Harvested 60% commercial clams, no breakage of marketable clams with short nozzle, some mortality with long nozzle	Created a track that remained soft for a few days and was an inch or two lower than undisturbed flat	N/A	N/A	MacPhail 1961a

Table 1b, continued. Dredging effects reported from research studies on the soft-shell clam, *Mya arenaria*. N/A indicates no data.

Intertidal flats	Mechanical escalator dredge	Clam Harbour, Nova Scotia Canada	Initial tests dredge harvested 90% of small clams, 50% of commercial sized, some mortality of seed clams by smothering and overcrowding, after dredging little to no damage to shellfish	Dug deep trenches in shallow water	Only 7-10% were too damaged to rebury after 3 hours	N/A	MacPhail 1961b
Fine sand	Hydraulic clam rake	Clam Harbour, Nova Scotia Canada	Damage to <5% of marketable clams and <5% of small clams remaining after harvest, sand and grit in mantle cavity of clams, shell breakage <1%	Liquefied upper soil strata into soil-water suspension, tracks 24 inches wide, 2.5 in deep, poor operation can excavate wells in sediment	N/A	N/A	MacPhail and Medcof 1962
Oyster beds and clams on soft sediment	Hydraulic clam dredge	Maryland	Intensive dredging: mortality of oysters in dredge zone and 25 ft downstream, no mortality of oysters or spat 75 ft beyond dredge, few clams broken, increase in predatory fish and crabs, dredging not a hazard to tidewater resources away from oyster beds	Intensive dredging elevated turbidity and caused redeposition of suspended sediment 75 ft downstream, trenches up to 18 in deep but more typically 2-8 in	N/A	Trenches 4-6 days after dredging 3 inches deep, recovery variable, sediments may take months to compact, dredged areas continue to repopulate with clams	Manning 1957
Subtidal assorted sediments	Maryland soft shell clam dredge	Maryland	No damage to fish or blue crabs, about 1% breakage of collected clams, reduced number of market sized clams, some breakage of fragile animals in collection baskets at end of conveyer, fish attracted to dredge track due to food availability	Sediment dislodged from the bottom, and falls through the conveyer or brought to the surface	N/A	After 7 yrs of harvesting, no evidence of impaired reproduction or replacement of stocks	Manning 1960

Table 1b, continued. Dredging effects reported from research studies on the soft-shell clam, *Mya arenaria*. N/A indicates no data.

Clam flat, clean sandy soil	Hydraulic rake	Clam Harbour, Nova Scotia, Canada	Damage to <5% of the catch and <5% of the clams left behind	Upper substratum is converted to a soil-fluid mixture, track width measured 33 in, track was firm after 24 hours, nozzle settings determine track width	N/A	N/A	Medcof and MacPhail 1962
Intertidal beaches, sandy flats	Maryland style hydraulic escalator clam dredge	Clam Harbour, Nova Scotia, Canada	Clams returned after dredging settled on the surface, not buried or smothered, breakage to 7-10% of clams, 90% of small clams returned within 75-100 ft of where they entered the dredge, clams reburied quickly	Heavy "soil" settled first in tracks, tracks 50-75 in. wide with surfaces 4-6 inches below adjacent levels, crumbling and erosion of tracks with extended widths	N/A	N/A	Medcof 1961
Medium to fine sands	Maryland hydraulic escalator clam dredge	Potomac River, Maryland	Small clams overcame dredging effects better, sublegal clams not significantly reduced by dredging, recruitment of young clams increased, where number of adults was reduced by dredging	No major changes to sediment structure or grain size after dredging	Organic carbon in first inch of substrate redistributed and concentrated after dredging	Dredged bottom soft for 1 year, March and June dredging showed no difference in clam (>35 mm) densities after 4 months, August dredging: differed for 8-12 months	Pfitzenmeyer 1972a, 1972b
Sand to sandy mud	Hydraulic dredge	Chester River, Tributary to Chesapeake Bay, Maryland	Increased turbidity and light attenuation from dredging decreased light penetration impacting SAV, SAV tolerated reduced light for a day or two of clamming beyond that negative impacts	Plumes: significantly higher turbidity/light attenuation than background, decreased sediment compaction due to sediment type and water depth, plume dissipation linked to grain size	N/A	Plumes dissipated exponentially, rapidly at first as coarse particles settle, slowly for fine sediments, plumes in shallow water slower decay	Ruffin 1995

Table 1c. Dredging effects reported from research studies on harvest fishery of deepwater North and Mid-Atlantic clam species. N/A indicates no data.

Species	Habitat Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Recovery	Author
Arctic surfclam, *Mactromeris polynyma*	Medium grained sandy bank	Two hydraulic clam dredges, 4 m wide, 12 tons	Banquereau, Scotian Shelf, southeast Atlantic Canada	Density of large burrows reduced by 90% due to mortality of clams, polychaete tubes reduced, removal of empty shell from benthos	Sediment smoothing, dredge created 20 cm deep, 4 m wide curvilinear furrows, margins degraded by slumping, sediment transport and bioturbation	N/A	Lasting effects on sediment structure, no recovery of large burrows at 3 yrs, dredge tracks persist for 3 yrs, increase in polychaete tubes at 2 yrs, at 3 yrs 100% increase over predredge numbers	Gilkinson et al. 2003
Cyrtodaria siliqua, Arctica islandica, M. polynyma, Serripes groenlandicus	Medium grained sandy seabed	Two hydraulic clam dredges 4 m wide, 12 tons	Banquereau, Scotian Shelf Eastern Canada	40% decrease in macrofaunal abundance in furrows, damage to some clams, reduced biomass of target species, colonizing on-going for 2 years	Cutting depth to 20 cm	N/A	Marked increase in polychaete and amphipod abundance at 1 yr, opportunistic species increased by >100%, taxonomic distinctness declined, no recovery of target species at 2 yrs	Gilkinson et al. 2005
Arctic surfclam, *M. polynyma*	Sand with some rocks	New England hydraulic dredge	Gulf of St. Lawrence, Canada	Damage to <10% of surf clams, 50% of razor clams and a small number of other mollusks, 2/3 of clams remained on bottom, no long or short term harm to resident benthic species	Depth of impact 15 to 30 cm, sediment suspended for up to 30 minutes, sediments in tracks less compacted than adjacent areas	N/A	N/A	Lambert and Goudreau 1996

Table 1c, continued. Dredging effects reported from research studies on harvest fishery of deepwater North and Mid-Atlantic clam species. N/A indicates no data.

Ocean quahog, *Arctica islandica*	Very fine to medium sand, recently fished and abandoned bed, currently fished and unfished control	Hydraulic dredge	Continental shelf off coastal New Jersey	Abundance and species composition of benthic macroinvertebrates was not altered by dredging	Dredged areas had small shell fragments and gravel on the sand surface caused by resorting of sand by water jetting	N/A		MacKenzie 1982
Atlantic surfclam, *Spisula solidissima*	Fine, medium, and silty sands	1.2 m Hydraulic clam dredge	Offshore of Rockaway Beach, southwest Long Island New York	Predators more abundant in dredge track, densities back to normal after 24-hrs except moon snails increased, mortality was 30% when dredge efficiency was high	Initial dredge track conspicuous with smooth track shoulder, angled walls and a flat floor	N/A	Dredge tracks deteriorated rapidly and after 24 hrs became shallow depressions	Meyer et al. 1981

Table 1d. Dredging effects reported from research studies on assorted clam species in Florida. N/A indicates no data.

Target Species	Habitat Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Recovery	Author
Southern Quahog, *Mercenaria campechiensis,* Southern surfclam, *Spisula raveneli,* Sunray Venus clam, *Macrocallista nimbosa*	Variable sediment and seagrass	Maryland hydraulic escalator clam dredge	Tampa and Boca Ciega Bays, Cedar Keys, Tarpon Springs, Florida	No recolonization of seagrass turtlegrass *Thalassia testudinum* and *Syringodium filiforme,* no increase in clam set, no differences in fauna between dredged and control	Water jets penetrated to 18 inches, uprooted vegetation, tracks visible from 1- 86 days, some areas soft for >500 days, decrease in silt/clay after dredging	N/A	Some regrowth of alga *Caulerpa prolifera* at 86 days post dredging, trenches in sand filled in immediately, decrease in silt/clay resolved within a year	Godcharles 1971
Sunray Venus clam, *M. nimbosa*	Sandy substrate	Commercial hydraulic Nantucket clam dredge	northwest coast Florida	Dredging damaged beds of turtle grass, excessive hydraulic pressure forced organisms under cutting blade damaging them	Dredge filled rapidly with mud disturbing surface layers	N/A	N/A	Jolley 1972
Sunray Venus clam, *M. nimbosa*	Loose quartz sand	Nantucket hydraulic dredge	Bell Shoal, St. Joseph Bay, Florida	Numbers of fish increased after passage of the dredge, some shell breakage, overall operation of dredge was not harmful to marine environment, by-catch included other commercial clam species	Substrate was churned up to free clams	N/A	N/A	Stokes et al. 1968

Table 1e. Dredging effects reported from research studies on the Manila clam, *Ruditapes philippinarum*. N/A indicates no data.

Habitat Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Time to Recovery	Author
Firm coarse substrate with rocks	Hydraulic escalator dredge	British Columbia	Decline in harvest size clams, some mortality of legal and sublegal clams	Trenches 0.5 m deep, 2 m wide at 2-4 months, deep holes, mounds of side cast material 30 cm deep, empty shells	N/A	No significant clam recovery 16 months postharvest	Adkins et al. 1983
Soft bottom, clay	Rusca (iron cage) and rotating drum (iron) teeth rotate and wash clams from drum to conveyer	Venice Lagoon, Italy	Disturbance of benthic community, bottom sediments became azoic, decrease in abundance of benthic organisms	Resuspension of top sediment layer, brought deep anoxic layer near the bottom, harvest gear extends 10 cm deep, changes to sediment compaction	Depletion of oxidized sediment layer, effects on redox conditions Likely to affect nitrogen and phosphorus cycling	N/A	Badino et al. 2004
Sand silt clay	Simulated sediment dredging	Sacca di Goro, Italy	Not measured with regard to simulated dredging	Resuspension of surface sediment, cultivated sediments more reduced than control	Rapid depletion of oxygen in water overlying sediments	N/A	Bartoli et al. 2001
Intertidal sandflats, *Lanice conchilega* beds	Tractor-towed sifter	Chausey archipelago Normandy France	Decreased densities of worm *L. conchilega* and abundance and diversity of macrofauna	Sifted top 10 cm of substrate	N/A	N/A	Godet et al. 2009
Mud flat with clay, fine sand and silt	Suction dredge	Southeast England	Reduction in density of individuals, number of species and diversity	Removed larger sand fractions down to the underlying clay substrate, sediment resuspended by dredge, exposing clay	N/A	No difference in infaunal communities in dredge and control areas by 7 months, sediment structure restored by sedimentation	Kaiser et al. 1996

Table 1e, continued. Dredging effects reported from research studies on the Manila clam, *Ruditapes philippinarum*. N/A indicates no data.

Silty-sand	Hydraulic dredge	Venice Lagoon near port of Malamocco Italy	Nonselective reduction in species abundance, both those captured and those resuspended in the sediment plume and transported by currents	Produced deep 20 cm furrows affecting texture of the bottom	N/A	After 60 days, non-opportunistic species assume opportunistic behavior during initial recolonization in dredge areas	Pranovi et al. 1998
Lagoon	Mechanical rusca (iron cage) dredge	Venice Lagoon, Italy	Enhanced clam growth, negative effects on some benthic invertebrates and detritivorous fish, positive effects on macrophytal grazers, reduced macroalgae	Resuspended sediments provide a food source for clams, especially juveniles, decreased light transmittance and water transparency	Removal of bioturbators affects sediment biogeochemistry since harvesting is a strong mixing force	N/A	Pranovi et al. 2003
Transition from silt/ silt-clay (15 years ago) to sand or silty-sand	Hydraulic dredging	Central Venetian Lagoon, Italy	Significant changes in total abundance and biomass, no *Zostera* colonization and diffusion, scavengers increased	Furrow 8- 10 cm deep, no immediate changes in sieve fractions, long term effects on sieve fractions from loss/redistribution of fine sediments	N/A	Furrows visible for 2 months, differences in biological community for 60 days, long term changes in particle size and sediment texture	Pranovi and Giovanardi 1994
Muddy sand	Suction harvesting	River Exe, Devon, United Kingdom	Invertebrate abundance and species diversity reduced by >90%	Increased sediment load in water, 10 cm deep trench	Suspended particles settled downstream, dispersed to background levels 40 m from dredge	Rapid recovery of invertebrates (spring recruitment) within 8 months of harvest, trenches refilled in 3-4 months	Spencer 1997
Muddy sand	Suction dredge	River Exe, Devon, United Kingdom	Immediate 80% reduction in infaunal species abundance	Created 10 cm deep trenches which took 2-3 months to refill	N/A	Sediment structure and invertebrate infaunal community recovered by 12 months	Spencer et al. 1996, 1997, 1998

Table 1f. Dredging effects reported from research studies on clam species from Portugal. N/A indicates no data.

Target species	Habitat Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Recovery	Author
Spisula. solida, Donax trunculus, Venus striatula, Pharus legumen, Enis siliqua	Soft-bottom	Portuguese dragged, toothed iron clam dredge	Algarve coast, South Portugal	Decrease in abundance of meiofauna and macrofauna, target and fragile taxa predators increased	Dredge penetrated up to 50 cm depth, sediment redistribution	N/A	N/A	Alves et al. 2003
S. solida D. trunculus, V. striatula, P. legumen, E. siliqua	Sand	Dragged iron bivalve dredges	Algarve coast, south Portugal	Macrofaunal distribution, diversity, evenness, number of taxa and abundance varied across dredge track	A sand buffer formed in front of the dredge mouth pushing sediment sideways	N/A	N/A	Chícharo et al. 2002a
S. solida	Sandy sediment grain sizes 0.5 and 0.355 mm	Dragged iron bivalve dredges	Algarve coast, south Portugal	Increased number of exposed clams, predators increased 6-9 min after dredging: *Ophiura texturata, Pomatochistus spp., Diogenes pugilator, Nassarius reticulatus*	N/A	N/A	N/A	Chícharo et al. 2002b
S. solida	Simulated sand dredge tracks	Laboratory simulated bivalve dredge	Algarve coast, south Portugal	Sublethal effects on clams: decreased RNA/DNA and N/P lipid ratio, decline in condition	N/A	N/A	Clam condition improved after spawning season	Chícharo et al. 2003

Table 1f, continued. Dredging effects reported from research studies on clam species from Portugal. N/A indicates no data.

S. solida, D. trunculus	Coarse sand and gravel	Towed clam dredge	Algarve, southern Portugal	Impacts greater at 18 m depth: macrobenthic organisms showed reduced abundance, number of taxa, and diversity, decrease in meiofauna abundance number of taxa	Sediment morphology and texture affected, dredge track measured 30 cm wide and 10 cm deep	N/A	Faster biological recovery at 6 versus 18 m, meiofauna recovered by 35 days, tracks at 6 m gone after 24 hrs but still visible at 18 m for 13 days, at 6 m grain size was similar to control by 17 days, at 18 m 1 day after dredging, slight increase in grain size, by 13 days dredged similar to control	Constantino et al. 2009
S. solida, D. trunculus, E. siliqua, P. legumen	Shallow sandy	Mechanical metal bivalve dredge	Vilamoura and Armona, Algarve coast, Portugal	N/A	Formation of a furrow exposing underlying sand with a spoil ridge on either side of the depression	Porewater nitrates, ammonium, organic nitrogen, phosphate and silicate decreased post-dredging and increased in near bottom water	Reestablishment of the seabed was reached within a short time at both stations	Falcão et al. 2003
Chamelea gallina, D. trunculus, S. solida, Tellina tenuis	Sand and sandy-mud bottom	Portuguese clam dredge	Lagos in South Portugal	Low damage and mortality of macrobenthic animals in dredge path, scavengers attracted in high densities, but dissipated rapidly	Suspended sediment settled rapidly in sand and mud, tracks deeper and more persistent in sandy mud , tracks eroded via wave action and currents	N/A	Undamaged or slightly damaged shellfish reburied immediately after escaping the dredge	Gaspar et al. 2003

Table 1g. Dredging effects reported from research studies on the Striped Venus clam *Chamelea gallina*. N/A indicates no data.

Habitat Sediment	**Harvest Gear**	**Study Location**	**Biological Effects**	**Physical Effects**	**Chemical Effects**	**Recovery**	**Author**
Two sites: sand vs. mud	Hydraulic dredge using high and low water pressure	North Adriatic Sea	High pressure treated clams had lower adenylate energy charge than low pressure, high pressure treated clams burrowed less	Grain size influenced speed and operation of dredge, impacts were greater on mud bottom	N/A	Juvenile clams returned to water after dredging reburrow slowly and are subject to predation	Da Ros et al. 2003
N/A	Dredging with high pressure water jets with sieve sorting versus low pressure water jets	Lido coast, Lagoon of Venice, Adriatic Sea	At high pressure clam filtration rates decreased , respiration rates increased, lower scope for growth, hematocrit and phagocytic index decreased, reduced acid phosphotase and increased β-glucuronidase activity	N/A	N/A	N/A	Marin et al. 2003
Fine sand	2.4 -3 m wide, 0.6 - 0.8 ton hydraulic dredge	Adriatic Sea, Italy	No effects to macrobenthic community (polychates, crustaceans, detritivores and suspensivores), mollusks and bivalve *Abra alba* were affected, short term pulse impact on scavengers and predators	N/A	N/A	N/A	Morello et al. 2005
Fine sand	Hydraulic clam dredge	Adriatic Sea, Italy	Depth strata and fishing intensity affected dredge impact, moderate disturbance to benthic community and significant difference in species number and evenness between fishing intensity at 4-6 m, reduction in evenness at high intensity, increased species number with decreasing intensity	N/A	N/A	Recovery of benthic community within 6 m	Morello et al. 2006

Table 1g, continued. Dredging effects reported from research studies on the Striped Venus clam *Chamelea gallina*. N/A indicates no data.

Jesolo; fine sand, Lido; medium grain sand	Hydraulic dredge, high and low pressure without sorting, high pressure with sorting	Jesolo and Lido, Northern Adriatic Sea, Italy	Water pressure and sorting increased shell damage, the larger the clam the more damage it sustained, some clams survived damage	N/A	N/A	N/A	Moschino et al. 2002, 2003
Jesolo; fine sand, Lido; medium grain sand	Hydraulic dredge, high and low pressure without sorting, high pressure with sorting	Jesolo and Lido, Northern Adriatic Sea, Italy	High water pressure and mechanized sorting decreased clearance rates, scope for growth, and survival in air, season may increase affects	N/A	N/A	N/A	Moschino et al. 2008
N/A	Experimental hydraulic dredge with vibrating bottom grid	Adriatic Sea North of port of Giulianova, Italy	As compared to standard gear: larger number of damaged shells, better size selectivity and escape of undersized clams and discarded fauna, reduced by-catch, enhanced quality of commercial product	N/A	N/A	N/A	Rambaldi et al. 2001

Table 1h. Dredging effects reported from research studies on the razor clam, *Ensis* sp. N/A indicates no data.

Habitat Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Recovery	Author
Clam bed	Hydraulic dredge	Gormanston, Irish Sea	Reduced dominant and target species, increased infaunal community diversity, increase in scavengers and predators, *Lanice conchilega* tube worm eliminated, *E. siliqua* replaced by suspension feeder *Lutraria lutraria*	Dredging to 30 cm deep, increase in larger grain sizes and sorting coefficients, high content of broken shell	N/A	Initial increase in diversity, followed by a downward trend	Fahy and Carroll 2007
Clean sandy bottom	Two dredges, varying tooth lengths	Lagos, south Portugal	10-15% by-catch damage to clams reduced by increased tooth length and decreased tow duration, injury inversely proportional to catch efficiency	Physical impact of dredge of short duration	N/A	Dredge tracks erased within 24 hrs	Gaspar et al. 1998
Sand	Hydraulic suction dredging	Loch Gairloch, Ross-shire, Scotland	Reduction in target species, increased scavengers, reduced number of macrofaunal species and individuals after 1 day	Physical disturbance, trenches and holes, area affected 20-30%	N/A	Trenches and holes resolved within 40 days, macrofauna recovered by 40 days	Hall et al. 1990
Maerl	Hydraulic blade dredge	Clyde Sea, Scotland	Kelp coated with mud, both seaweed and sessile biota buried with silt, fragile organisms damaged, increase in predators post-dredging	Changed from sandy gravel to gravelly sand, suspended sediment reduced visibility, dredge track formed, snow-plough effect, altered sediment to 9 cm	N/A	Sediment settled within 1hour, track partially eroded within 1month, depth and width reduced by wave action	Hauton et al. 2003a
Sand	Hydraulic blade dredge	Clyde Sea, Scotland	Survival of 60-70% of dislodged fauna mostly urchin *Echinocardium cordatum,* 20-100% of target clams damaged	Tracks of fluidized sand beds	N/A	Reburial of 80-90 % of clams within 30 min, a few still unable to rebury after 3 hrs	Hauton et al. 2003b

Table 1h, continued. Dredging effects reported from research studies on the razor clam, *Ensis* sp. N/A indicates no data.

Coarse sand and shell	Hydraulic dredge	Clyde Sea, Scotland	Some damage of larger versus clams	Dredged area 45 cm swath, 80 cm disturbed, surface width of dredge track was 1.01 m	N/A	N/A	Hauton et al. 2007
sand	Hydraulic dredge	Clyde Sea, Scotland	N/A	Suspended fine sediment into water column, resettled in dredge track, sediment reduced from moderately to poorly sorted, dredge left 13.9 cm tracks of fluidized sand, eliminated stratification, sediments vertically homogenous to 20 cm	N/A	After 100 days, wave action and bioturbation reduced tracks to 2.9 cm depth, tracks now shallow furrows, width increased from 100- 115 cm	Hauton and Paterson 2003
Fine sand and open broken shell	Suction dredging	Orphir Bay and Bay of Ireland, Orkney Islands, United Kingdom	Lower density and smaller mean length of clams from dredged area, breaks in shell margin, sand grains embedded in deep clefts in the shell matrix	N/A	N/A	Some clams showed slow initiation of escape digging and increased vulnerability to predator attack	Robinson and Richardson 1998
Sand	Water jet dredging	Outer Hebrides-Western Isles, United Kingdom	Initial removal of infauna, damage to 10-28%, scavengers attracted to tracks, immediate reduction in number of species, individuals, and biomass, no change in diversity, reduced polychaetes, increase in amphipods, damage to large bivalve by-catch	Immediate physical effects apparent, visible dredge tracks up to 2 m wide, fluidized sediment, reduction in % silt immediately after dredging, elevated turbidity	N/A	Dredge tracks refilled after 5 days, and were no longer visible at 11 weeks, sediment remained fluidized, % silt returned to normal at 5 days	Tuck et al. 2000

Table 1i. Dredging effects reported from research studies on Pacific Northwest clam species. N/A indicates no data.

Target Species	Habitat Sediment	Harvest Gear	Study Location	Biological Effects	Physical Effects	Chemical Effects	Recovery	Author
Saxidomus gigantea, Leukoma staminea, R. philippinarum	Firm coarse substrate with rocks	Hydraulic escalator harvester	British Columbia	Decline in harvest size clams, mortality of legal and sublegal clams	Trenches 0.5 m deep, 2 m wide at 2-4 months, deep holes, mounds of side cast material 30 cm deep, empty shells	N/A	No significant clam recovery 16 months postharvest	Adkins et al. 1983
S. gigantea, P. stamina, Tresus capax, Tresus nuttallii	Sand, gravel and shell substrate	Hydraulic escalator harvester	Agate Passage, Puget Sound, Washington	Reduced abundance of attached kelp, little effect on number of benthic species, reduced number of individuals and weight of organisms	Changes in substrate distribution, shell left on substrate surface, no effects on percentage of fine substrate	Chemical measurements in harvested areas were reduced or unchanged versus control likely due to reduced biomass	Most species recovered to control levels within 2 yrs	Goodwin and Shaul 1978
S. gigantea, P. staminea	Sand, gravel and shell, some eelgrass beds (which dredge avoided)	Hanks hydraulic escalator harvester	Puget Sound, Washington	Smothering of some adult clams	Visible tracks and furrows, decrease in sediment compactness, transient sandbar, loosening, emulsification and loss of vertical stratification	N/A	Beach recovered in 1.5 yrs, tracks no longer visible, good clam set	Goodwin and Shaul 1980

Table 2. Dredging effects reported from research studies on the Eastern oyster *Crassostrea virginica*. N/A indicates no data.

Habitat Sediment	Harvest Gear	Study Location	Biological impacts	Physical Impacts	Chemical impacts	Recovery	Author
Intertidal	Mechanical oyster harvester	South Carolina	No detectable damage to oyster shell matrix, 5% of harvested oysters were damaged	N/A	N/A	N/A	Collier and McLaughlin 1983 (abstract)
Oyster bottom	Hydraulic escalator dredge	Patuxent River, Maryland	Minor effect of heavy particles on oysters within 15 ft of dredging, infauna not significantly reduced in dredge and impact areas, no affect on juvenile clams, 100% mortality and burial of oysters in dredged area, disruption of epibenthic community	Substrate surface color was lighter than on undisturbed bottom, troughs and ridges in dredged area, suspension of sediment high compared to background, no significant change in particulate fraction in impact area	No toxic substances detected after dredging	Reestablishment of infauna in dredged area rapid, 3 days after dredge no alteration of bottom, no accumulation of displaced substrate, no burial of oysters or cultch	Drobeck and Johnson 1982
High and low intertidal oyster reefs	Mechanical oyster harvester	Beaufort County, South Carolina	Oyster biomass declined in high and low intertidal, species density correlated with oyster biomass, reduced faunal density in high intertidal with target species number and frequency unaffected by harvest, diversity and evenness in harvested high intertidal > than control	Some areas appeared undisturbed, others had tracks and deep depressions	N/A	Oyster biomass in high intertidal remained low, oyster spat were attracted after harvest	Klemanowicz 1985, Manzi et al. 1985

Table 3. Dredging effects reported from research studies on the blue mussel, *Mytilus edulis*. N/A indicates no data.

Intertidal sublittoral	Dutch and Baird dredges	Menai Straits, North Wales	Shell damage to 13% of mussels from rotary sorting and 1.6% damaged by dredging, up to 5% of small mussels destroyed by dredge and sorting induced shell fractures	N/A	N/A	Mussels with light damage were still alive 72 hours after sorting	Dare 1974
Two sites, sand and mud	2-3 m width single commercial dredge and otter trawls	Lower Narragansett Bay and Rhode Island Sound, Rhode Island	N/A	Scars from dredging and trawling are short lived in sand and shoal waters and longer lasting in deep water and mud	N/A	Bottom scars in shallow sand substrate resolved in 1 to 4 days, 60 days in deep mud substrate	DeAlteris et al. 1999
Mussel beds with bare mud flats	Dutch mussel dredge, 1.8 m wide, 250 kg	Danish Sound, Limfjorden, Denmark	Reduced density of polychaetes, reduced species number, increase in shrimp *Crangon crangon*	Dredging formed 2-5 cm deep furrows, no change to sediment texture or organic content	N/A	Reduced species number in dredge area lasted 40 days, increase in species number outside dredge area for 7 days	Dolmer et al. 2001
Mud, silt and clay	Commercial mussel dredge	Maquoit Bay, Maine	Dragging disturbed 10% of eelgrass in study area, removing plant materials above and below ground	Dragging did not affect physical characteristics of the sediment	N/A	After 1yr eelgrass shoot density, height and total biomass reduced, reduced biomass persisted for >7 yrs , pattern and rate of recovery proportional to drag intensity	Neckles et al. 2005

Table 4. Dredging effects reported from research studies *on the cockle Cerastoderma* edule. N/A indicates no data.

Habitat Sediment	Harvest Gear	Study Location	Biological Impacts	Physical Impacts	Chemical Impacts	Recovery	Author
Two sites, mud and sand, intertidal	Tractor towed cockle harvester	Burry Inlet, Wales	Loss of common invertebrates, decreased species richness at both sites, dominance declined in sand area, community in clean sand recovered more quickly than mud	Physical disruption to the complex layered structure of the sediment	Anoxic layer was brought to the surface and dispersed	Modest recovery occurred in sand, in mud *Pygospio elegans* and *Hydrobia ulvae* (gastropods) remained depleted for 100 days, Nephtys *hombergi* (polychaete), *Scoloplos armiger* and *Bathyporeia pilosa* (amphipod) for 50 days	Ferns et al. 2000
Silty sediments, coarser toward center of bay	Hydraulic suction dredge and tractor dredge	Auchencairn Bay, Dumfriesshire Scotland	High mortality of nontarget benthic fauna, considerable survival in suction dredged areas, reduced abundance of individuals and species	Dredge tracks did not persist	N/A	Faunal structure in suction dredged plots recovered by 56 days	Hall and Harding 1997
Intertidal flats	Suction dredge	Dutch Wadden Sea	Densities of *M. balthica* lower in dredged areas, reduction in density of non-target species	Sediment removed and disturbed by dredging, less suitable for settlement by *Macoma balthica* and *Mytilus edulis*	N/A	Densities of nontarget fauna lower in dredged areas up to 1 yr later	Hiddink 2003
Sandy intertidal flats	Suction dredge	Griend, Dutch Wadden Sea	Significant negative effect of dredging on settlement of cockles, declines in bivalve stocks linked to reduced settlement	Dredging increased sediment grain size while silt was lost	N/A	Initial sediment characteristics returned,, long lasting (8 yr decline) negative effects on bivalve recruitment	Piersma et al. 2001

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Publications and Reports of the Northeast Fisheries Science Center

The mission of NOAA's National Marine Fisheries Service (NMFS) is "stewardship of living marine resources for the benefit of the nation through their science-based conservation and management and promotion of the health of their environment." As the research arm of the NMFS's Northeast Region, the Northeast Fisheries Science Center (NEFSC) supports the NMFS mission by "conducting ecosystem-based research and assessments of living marine resources, with a focus on the Northeast Shelf, to promote the recovery and long-term sustainability of these resources and to generate social and economic opportunities and benefits from their use." Results of NEFSC research are largely reported in primary scientific media (*e.g.*, anonymously-peer-reviewed scientific journals). However, to assist itself in providing data, information, and advice to its constituents, the NEFSC occasionally releases its results in its own media. Currently, there are three such media:

NOAA Technical Memorandum NMFS-NE -- This series is issued irregularly. The series typically includes: data reports of long-term field or lab studies of important species or habitats; synthesis reports for important species or habitats; annual reports of overall assessment or monitoring programs; manuals describing program-wide surveying or experimental techniques; literature surveys of important species or habitat topics; proceedings and collected papers of scientific meetings; and indexed and/or annotated bibliographies. All issues receive internal scientific review and most issues receive technical and copy editing.

Northeast Fisheries Science Center Reference Document -- This series is issued irregularly. The series typically includes: data reports on field and lab studies; progress reports on experiments, monitoring, and assessments; background papers for, collected abstracts of, and/or summary reports of scientific meetings; and simple bibliographies. Issues receive internal scientific review, but no technical or copy editing.

Resource Survey Report (formerly *Fishermen's Report*) -- This information report is a quick-turnaround report on the distribution and relative abundance of selected living marine resources as derived from each of the NEFSC's periodic research vessel surveys of the Northeast's continental shelf. There is no scientific review, nor any technical or copy editing, of this report.

OBTAINING A COPY: To obtain a copy of a *NOAA Technical Memorandum NMFS-NE* or a *Northeast Fisheries Science Center Reference Document*, or to subscribe to the *Resource Survey Report*, either contact the NEFSC Editorial Office (166 Water St., Woods Hole, MA 02543-1026; 508-495-2228) or consult the NEFSC webpage on "Reports and Publications" (*http://www.nefsc.noaa.gov/nefsc/publications/*).