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The benthic community of the eastern US continental shelf: A literature synopsis of benthic faunal resources

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Abstract

The existing scientific literature on offshore benthic assemblages (OBA) residing along the US East and Gulf of Mexico continental shelf was reviewed. Identification was made of any associations between the dominant OBA and particular sediment types and/or bathymetry. Of special interest was the evaluation of reported effects of sand dredge/mining activities on the dominant OBA and recognition of data deficiencies. One hundred and twenty-two references were selected and classified as to type of study with pertinent results extracted. Polychaetes were predominantly cited as the principal infaunal taxa present in studies from both the Gulf of Mexico and US Atlantic coast. Specifically, *Prionospio cristata*, *Nephtys incisa*, *N. picta*, and *Spiophanes bombyx* were consistently identified as a common part of the benthic community structure. Surveys from the East Coast indicated a greater diversity of dominant taxa not reported for the Gulf of Mexico than vice-versa. Robust animal–sediment or animal–depth relationships were not readily available. From the few studies available, it appears that general "recovery" from anthropogenic disturbance by benthic assemblages on the continental shelf occurs within three months to 2.5 years. Presently, it is difficult to draw conclusions about approximate benthic faunal recovery times following anthropogenic activities such as sand mining and/or disposal operations because of the paucity of studies.

Keywords: Atlantic coast; Benthos; Continental shelf; Dredging; Gulf of Mexico; Infauna; Macrofauna; Sand mining

Contents

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1. Introduction

Benthic habitat on the continental shelf is not a homogeneous region of flat mud habitat, but also contains natural bathymetric highs that includes ridge and shoal features. Accordingly, the distribution of benthos residing in this area therefore is not uniform, but rather patchily distributed. Sand areas on the continental shelf provide habitat for many benthic infaunal organisms (e.g., polychaetes, bivalves, amphipods; Hobbs, 2002; Posey et al., 1998) with a species diversity and abundance of infauna comparable to nearshore and intertidal areas (Posey et al., 1998). Many of the natural ridge/shoal features found on the continental shelf have been identified as containing exploitable sand deposits. For example, it is estimated that Ship Shoal, located off of Louisiana, contains 1.6 billion cubic yards of sand appropriate for beach renourishment and land stabilization projects (Research Planning Inc. et al., 2001). The sediments mined from offshore sources are being used to meet demands for beach renourishment, repair storm damage, prevent erosion, and prevent wetland loss due to anthropogenic alteration and sea-level rise (Research Planning Inc. et al., 2001). As nearshore reserves become depleted, offshore sand resources such as Ship Shoal are becoming more important (EMSAGG, 2003). Benthic infauna are directly tied to the substrate in which they live (e.g., Alexander et al., 1981) and thereby, benthic communities are highly susceptible to anthropogenic activities that directly or indirectly alter the sediment environment (e.g., sand mining). Thus, it is important to identify and summarize what benthic infaunal resources have been documented to exist on the continental shelf and how potential alterations to the resident benthic or epibenthic invertebrate communities may impact trophic and/or habitat relationships.

Several finfish species colonize offshore sand areas as juveniles, exploiting them for both habitat and feeding purposes. For example, juvenile red snapper have been found to utilize low-relief habitat (Szedlmayer and Conti, 1999), where their diet is dominated by small crustaceans and polychaetes common to sandy sediments (Szedlmayer and Lee, 2004). Other resident fishes, such as flatfish (e.g., flounder, sole) reside in sandy areas for their entire life cycle. Flatfishes tend to undergo an ontogenetic shift in their diet. As juveniles, flatfish feed primarily upon annelids, switching to crustacean and bivalve prey as they increase in size (Rijnsdorp and Vingerhoed, 2001). The presence of benthic assemblages is important not only as food for these organisms, but also for the sediment stabilization, biogenic structure, and nutrient turnover they provide. Biogenic structures (i.e., tube, mound, and burrows) constructed by invertebrates provide distinct habitat with which many juvenile fish have been found to utilize as a refuge from predation (Kaiser et al., 1999). If differences in the spatial distribution of the benthos could be explained based upon microhabitat features then the organisms that rely upon benthic organisms as food or structural resource may be linked to microhabitats as well.

The objectives of this study were to synthesize the existing benthic literature for the US East Coast and Gulf of Mexico Continental Shelves, and to identify the taxa composing dominant offshore benthic assemblages with special attention to any evidence regarding distinct sediment type or bathymetry associations. Of special interest were any investigations, which evaluated the effects of sand dredge/mining activities which may represent large scale disturbance in these areas.

2. Methods

The collection of information regarding benthic community structure, abundance, and biomass was carried out using electronic databases (e.g., Current Contents, First Search, Web of Science), standard Internet search engines (e.g., Google, Yahoo), and individual library searches (e.g., Minerals Management Service, Mote Marine Laboratory). Specific search details are available in Brooks et al. (2004). In general, 13 electronic databases were used in an intensive search of relevant sources from peer-reviewed literature. In addition, Internet search engines (e.g., Google, Yahoo) were used to search

for information available from individual US state agencies, and focused on information that was either unpublished or generally unknown outside of the specific agencies themselves. The literature-cited section of each acquired study was reviewed for any additional literature not found through the other search methods.

Literature to be included in the review was selected if it provided general benthic invertebrate community structure information in offshore areas in the Gulf of Mexico and western Atlantic Ocean (US East Coast) or any impacts of dredging operations on offshore benthic communities. Emphasis was given to literature with a focused study area within federal waters (i.e., 3 nautical miles or greater offshore for all coastal states except 5 for Texas and Florida). Some nearshore studies, and a few of estuarine nature, were included if their specific focus was on the impacts of sand mining. Studies which dealt solely with off-shore reef or hard-bottom fauna were excluded.

Relevant information on study sites, collection methods, results, and overall conclusions was extracted from each source. The type of study (ecological survey, experimental, or literature review), geographic area in which the study was conducted, relative spatial extent (m–kms), average depth range of the study, benthos collection method (e.g., sample processing, sieve size) utilized, environmental data (water parameters), habitat parameters (e.g., sediment particle size, habitat type), and the sampling season of collection was recorded for each study. When available the following information was recorded: (1) dominant taxa in terms of numerical abundance, (2) dominant taxa in terms of biomass, (3) spatial distribution patterns, (4) correlations with environmental parameter, (5) habitat parameter correlations, (6) post-disturbance fauna recovery times, (7) long-term differences between impacted versus non-impacted areas, and (8) details about dredging operations.

Any study in which a manipulation was performed (e.g., sediment colonization boxes, planned sediment disposal) was designated as an experimental study. If the natural fauna within an area was sampled, but no environmental manipulation was performed, the study was designated as a survey. Studies that synthesized the literature, but did not provide any new data were designated as review papers. Within the results section, the Gulf of Mexico and East Coast were divided into east–west and north–south regions, respectively, to extract any regional differences. We arbitrarily selected the Mississippi River to mark the separation of regions in the Gulf, while on the East Coast, the northern region was considered to be those states north of North Carolina and areas including and to the south of North Carolina are considered the southern East Coast region.

3. Results

3.1. General overview

Ninety-six references from 1954–2003, encompassing numerous peer-reviewed journal articles and governmental reports, were found (Table 1). Surveys were the most common type of study, representing over 50% of all of the papers reviewed, and over 75% of the studies from the Gulf of Mexico and East Coast. No survey studies included a comparison of fauna from the US East Coast to the Gulf of Mexico. In the Atlantic, the majority of the surveys were performed in the northern region while in the Gulf of Mexico, the majority of the surveys were exclusive to the area east of the Mississippi River. Additionally, five surveys spanned the review's pre-set geographical boundaries, with four of the surveys extending between the north and south East, and one survey conducted at sites in both the eastern and western Gulf of Mexico (Table 1). Twenty-four review papers were found with the majority from the eastern Gulf of Mexico and northern East Coast. One of the 16 reviews spanned geographical boundaries, with one covering the eastern and western Gulf of Mexico. No review paper was found which synthesized southern East Coast fauna. Five experimental studies were found with two conducted in the northern East Coast (one of these was in combination with a review) and another experimental study performed in the southern East Coast. There was also one experimental study, combined with a survey, spanning both the northern and southern East Coast. Within the Gulf of Mexico, there was one experimental study conducted in the eastern portion, but no experimental studies conducted in the western Gulf of Mexico (Table 1). Only survey and experimental papers were tabulated to examine patterns in the following sections of the results as review studies contain results found in the survey entries.

The depth of benthic surveys spanned 1–800 m in the Gulf of Mexico while surveys conducted in the

Table 1
A listing of all studies included in the review

Author (Date)	Study type	Geographic location	Author (Date)	Study type	Geographic Location
Alexander et al. (1981)	R	W	Jutte et al. (2002)	S	S
Applied Coastal Research and Engineering Inc., 2000	S	N	Lewis et al. (2001)	S	E
Auster et al. (1991)	S	N	The Louis Berger Group Inc. (1999)	R	N
Barry A. Vittor and Associates Inc. (1985)	R	E	Lyons and Collard (1974)	R	E
Bedinger (1981)	S	W	Mahadevan et al. (1976)	S	E
Berryhill (1977)	S	W	Mahadevan et al. (1984)	R	E
Blake (1978)	S	E	Marsh et al. (1980)	S	S
Blake et al. (1996)	S	E	Maurer and Leathem (1981)	S	N
Boesch (1973)	S	N	Maurer et al. (1976)	S	N
Boesch (1979)	S/E	N	Maurer et al. (1982)	S	N
Boesch et al. (1977)	S	N	McKinney and Harper (1980)	S	W
Bowen and Marsh (1988)	S	S	McNulty et al. (1962)	S	S
Burlas et al. (2001)	S	N	Messieh et al. (1991)	R	N
Byrnes et al. (1999)	E	E	Miller et al. (2002)	E/R	N
Byrnes et al. (2003)	S	S	Parker (1960)	S	W
Caracciolo and Steimle (1983)	R	N	Pearce (1970)	S	N
Carney (1993)	R	E/W	Pearce et al. (1981)	R	N
Cerame-Vivas and Gray (1966)	S	S	Phillips and James (1988)	R	W
Chang et al. (1992)	S	N	Phillips and Thompson (1990)	R	E
Collard and D'Asaro (1973)	R	E	Posey et al. (1998)	S	E
Collie et al. (1997)	S	N	Posey and Alphin (2002)	S	S
Conner and Simon (1979)	S	E	Powers et al. (2001)	S	W
Continental Shelf Associates (CSA) (1987)	S	E	Pratt (1973)	R	N
Cronin et al. (1998)	S	N	Rabalais et al. (2001)	S	W
Culter et al. (1992)	S	E	Ranasinghe et al. (1985)	S	N
Cutler and Mahadevan, (1982)	S	E	Ray (2001)	S	N
Cutler (1988)	S	E	Renaud et al. (1999)	E	S
Culter (1994a)	S	E	Rice and Culter (1984)	S	E
Culter (1994b)	S	S	Rice et al. (1981)	S	E
Cutler and Diaz (1998)	S	N	Rowe (1971)	S	N
Dauer (1980)	S	N	Saila et al. (1972)	S	N
Defenbaugh (1976)	S	E/W	Saloman (1974)	S	E
Emery and Uchupi (1972)	R	N	Saloman et al. (1982)	S	E
Emery et al. (1965)	S	N	Sanders (1968)	S	N
Environmental Science & Engineering Inc. et al. (1987)	S	E	Schaffner and Boesch (1982)	S	N
Escobar-Briones and Soto (1997)	S	W	Schaffner et al. (1996)	S	N
Finkl et al. (1997)	S	E	Shaw et al. (1982)	S	E
Fitzhugh (1984)	S	W	Sisson et al. (2002)	S	N
Flint and Holland (1980)	S	W	Steimle and Stone (1973)	S	N
Flint and Rabalais (1981)	S	W	Turbeville and Marsh (1982)	S	S
Giammona and Darnell (1990)	S	W	U.S. Environmental Protection Agency (1983)	R	E
Harper (1990)	S	E	Versar Inc. (1997)	S	N
Heard (1978)	S	E	Vittor (1978)	S	E
Hildebrand (1954)	S	W	Weston et al. (1982)	S	W
Hobbs (2000)	S	N	Wigley and McIntyre (1964)	S	N
Hobbs (2002)	R	N	Wigley and Theroux (1981)	S	N
Ivester (1978)	S	E	Woodward Clyde Consultants Inc. (1983)	S	E
Johnson and Nelson (1985)	S	S	Zajac and Whitlatch (2003)	E	N

The study type is listed for each study: Experimental (E), Review (R), or Survey (S). The location of each study along the United States East and Gulf Coast is listed: Northern East Coast (N), Southern East Coast (S), Eastern Gulf of Mexico (E), and Western Gulf of Mexico (W).

Table 2
Taxa which were highlighted as the dominant infaunal component in a given survey study

Taxa	East Coast	Gulf of Mexico	Total
Amphipods	North–2	East–2	4
	South–0	West–0	
Archiannellids	North–2	East–0	3
	South–1	West–0	
Asteroids	North–2	East–0	2
	South–0	West–0	
Bivalves	North–0	East–0	2
	South–1	West–1	
Foraminiferans	North–0	East–0	1
	South–0	West–1	
Gastropods	North–0	East–1	1
	South–0	West–0	
Nematodes	North–0	East–3	4
	South–0	West–1	
Polychaetes	North–8	East–15	31
	South–1	West–7	

East Coast ranged from 1–2500 m. Of the studies that specifically identified a dominant macrofaunal taxon, polychaetes were listed as the dominant taxon in 85% of the Gulf of Mexico surveys (Table 2). Amphipods were listed as the dominant taxon in 8% of the Gulf of Mexico studies, but only in the eastern region. While most papers only examined macrofauna, a few studies included meiofauna as well. In the Gulf of Mexico, nematodes were the dominant meiofauna found in the east, and foraminiferans in the western region. Information on numerical dominance by individual species was also available from a limited number of studies (Table 7: Brooks et al., 2004). Four polychaete taxa were identified as a predominant genus in five or more surveys (>20% of the survey studies) from the Gulf of Mexico, including *Paraprionospio*, *Mediomastus*, *Prionospio* and *Cossura. Paraprionospio pinnata* was the most commonly cited species (35%) in the Gulf of Mexico, which included surveys from both east and west of the Mississippi. *Cossura*, *Mediomastus*, *Nereis*, and *Prionospio* were all dominant polychaete genera commonly found from studies on both sides of the Gulf. *Sigambra tentaculata* and *Magelona phyllisae* were both common polychaete species, but only highlighted in surveys from west of the Mississippi River. In the Gulf of Mexico, two of the three most common amphipod taxa, *Acanthohaustorius sp.* and *Microdeutopus myersi*, along with the archiannelid, *Polygordius*, were only reported from the eastern Gulf of Mexico. *Ampelisca* was the predominant amphipod genera found in the Gulf (>10%) and was found both east and west of the Mississippi River. The bivalve, *Mulinia lateralis*, was the most commonly reported mollusk species in the Gulf.

As was true for the Gulf of Mexico, polychaetes were most commonly recorded as the dominant macrofauna found in surveys from the East Coast (Table 2). Specifically, 50% of the East Coast surveys with taxa information listed polychaetes as the dominant macrofaunal component. Polychaetes dominated in one of three surveys in the southern East Coast regions, with the remaining southern studies identifying bivalves and archiannelids as dominants. Archiannelids, asteroids, polychaetes, and amphipods were all dominant taxa reported in surveys from the northern East Coast. Spionidae polychaetes were the most frequently noted family within those East Coast surveys (47%) that specifically discussed numerically dominant species (Table 8: Brooks et al., 2004). At the genus level, *Spiophanes* was noted as a dominant genus in 47% of East Coast surveys, and more specifically, the species *Spiophanes bombyx*, was listed in 44% of surveys from both northern and southern regions. Species belonging to the polychaete genus, *Prionospio,* was found in 22% of the East Coast surveys, but generally only along the southern East Coast. Other common polychaete genera reported in at least four of the 32 East Coast studies (>10%) were *Chone, Clymenella*, *Lumbrineris*, *Nephtys*, *Nereis*, *Tharyx*, along with the families Aricidea, Sabellariidae, and Syllidae. *Ampelisca* and *Unicola* were the dominant amphipod genera, reported in 28% and 25% of the East Coast studies, respectively. The amphipod species, *Unicola irrorata,* was noted in 22% of the East Coast surveys. Other dominant amphipod genera reported in East Coast surveys were *Byblis*, *Erichthonius*, *Protohaustorius*, and *Pseudunciola*. The dominant bivalve genera reported in East Coast surveys included *Ensis*, *Nucula*, *Tellina*, and *Astarte*. Specifically, *Ensis directus* and *Nucula proxima* were commonly reported bivalve species. The predominant amphipod and bivalve taxa were similar to both the northern and southern East Coast regions. Other commonly encountered taxa (>10% of the East Coast surveys) included the archiannelid genus of *Polygordius,* the echinoid *Echinarachnius parma,* the decapod *Cancer irroratus,* and the tanaid genus, *Tanaissus* (*T. liljeborgi, T. psammophilus*).

The only dominant taxa found in both the Gulf of Mexico and East Coast were the polychaetes *Prionospio cristata*, *Nephtys incisa*, *N. picta*, and *S. bombyx*. Several dominant taxa from the East Coast were not reported as dominant in any surveys from the Gulf of Mexico including the amphipod species *Byblis serrata* and *U. irrorata*; the bivalve species *E. directus, Tellina agilis*; species from the bivalve genera *Astarte*, *Nucula;* the decapod *C. irroratus;* the echinoid *E. parma;* the polychaete species *Aricidea catherinae*, *A. neosuecia*, *A. philbinae*, *A. suecica*, *A. wassi*, *Chone infundibuliformis*, *Lumbrineris acuta*, *L. cruzensis*, *L. fragilis*, *L. impatiens*, *L. latreilli*, *L. testudinum*, and tanaid species *Tanaissus liljeborgi*, *T. psammophilus*. In contrast, the polychaetes *M. phyllisae*, *Mediomastus californiensis*, and *S. tentaculata* were reported as dominant in studies from the Gulf of Mexico, but not the East Coast.

3.2. Depth relationships

The majority of Gulf of Mexico surveys that discussed depth relationships indicated a decrease in faunal density with depth (Alexander et al., 1981; Berryhill, 1977; Blake, 1978; Environmental Science and Engineering Inc. et al., 1987; Flint and Holland, 1980; Harper, 1990; Ivester, 1978; Parker, 1960; Phillips and James, 1988; Phillips and Thompson, 1990). One study, however, noted that both macrofaunal density and diversity were greater offshore (20 km) than nearshore (8 km), indicating a positive association of density with depth (McKinney and Harper, 1980). Additionally, there were several surveys in which there was either no trend with macrofaunal density and depth (Culter et al., 1992), or relationships that were taxon or species-specific (Bedinger, 1981; Shaw et al., 1982). For example, Shaw et al. (1982) found organisms with restricted mobility to be less abundant inshore. Of the studies that discuss diversity or species richness in relation to depth, four noted a negative relationship (Berryhill, 1977; Blake, 1978; Parker, 1960; USEPA, 1983), three indicated a positive relationship (Cutler and Mahadevan, 1982, Flint and Holland, 1980; McKinney and Harper, 1980), and three other papers indicated no clear trend (Bedinger, 1981; Culter et al., 1992; Shaw et al., 1982). Thus, there appears to be no clear relationship between macrofaunal diversity and depth. Finally, only one study in the Gulf of Mexico investigated the relationship between benthic biomass and depth. A decrease of carbon biomass with increasing depth was reported (Collard and D'Asaro, 1973).

As with Gulf of Mexico surveys, East Coast surveys reported inconsistent relationships between macrofaunal density and depth. Three surveys indicated an increase in density with depth, either in polychaetes (Maurer and Leathem, 1981), sand assemblages (Steimle and Stone, 1973), or total macrofauna (Collie et al., 1997), but two other surveys reported a decrease in macrofaunal density with depth, on the continental slope (Boesch, 1979) and continental shelf (Wigley and McIntyre, 1964). Four surveys discussing the relationship of macrofaunal diversity and depth reported a positive relationship, with one study finding greater diversity on the continental slope than shelf (Emery and Uchupi, 1972), one showing an increase of polychaete diversity with depth down to 80 m (Maurer et al., 1976), and two others being more general in the nature of the link (Collard and D'Asaro, 1973; Steimle and Stone, 1973). Additionally, an increased diversity and species richness associated with the outer shelf and shelf-break was reported (Boesch, 1979). Two surveys on the East Coast discussed a negative relationship between biomass and depth (Emery and Uchupi, 1972; Watling and Norse, 1998). The one study documenting community composition cited changes in composition at depths of 32 and 115 m (Bergen et al., 2001).

3.3. Sediment–animal relationships

Overall, there was limited information on sediment properties (i.e., grain size, organic content) to compare with faunal diversity or abundance. Within the Gulf of Mexico surveys, four studies reported relationships between sediment type or grain size and community composition (Alexander et al., 1981; Vittor, 1985; Byrnes et al., 1999; Parker, 1960), and four relationships between sediment type and abundance measurements (Bedinger, 1981; Berryhill, 1977; Harper, 1990; Weston et al., 1982). However, only one found a local-scale relationship between community structure and sediment type (Parker, 1960). The majority of Gulf of Mexico studies indicated a lack of any strong relationship between sediment grain size and macrofaunal abundance (Environmental Science and Engineering Inc. et al., 1987), density (Fitzhugh, 1984; Phillips and Thompson, 1990), or community structure (Culter et al., 1992; Phillips and Thompson, 1990; Weston et al., 1982). Inconsistencies

across taxa or species were also noted on two occasions (Bedinger, 1981; Shaw et al., 1982).

In contrast to the Gulf of Mexico surveys, several relationships between grain size and fauna were observed in East Coast surveys. The use of discrete habitats, such as gravel (Byrnes et al., 2003; Emery et al., 1965), boulders (Environmental Science and Engineering Inc. et al., 1987), shell hash (Emery et al., 1965), coarse sands (Byrnes et al., 2003; Sisson et al., 2002), and fine sands (Sisson et al., 2002), was noted for macrofauna (Boesch et al, 1977; Byrnes et al., 2003), megafauna (Auster et al., 1991), polychaetes (Applied Coastal Research and Engineering Inc., 2000; Boesch, 1979; Byrnes et al., 2003), amphipods (Boesch, 1979), bivalves (Byrnes et al., 2003), tanaids (Byrnes et al., 2003), sand dollars (Sisson et al., 2002), and tubeworms (Sisson et al., 2002). In another study, however, temperature and salinity were found to influence the meiofauna community to a greater extent than sediments (Emery and Uchupi, 1972). Faunal abundance and sediment size were found to be related in three surveys (Emery et al., 1965; Rabalais et al., 2001; Wigley and Theroux, 1981). No correlation was found between sediment carbon or nitrogen and faunal abundance (Emery and Uchupi, 1972). An association between sediment and macrofaunal diversity was noticed in two instances (Boesch et al., 1977; Ranasinghe et al., 1985). Only one study related biomass to sediment characteristics, finding a relatively low biomass in shell hash habitat (Emery et al., 1965).

3.4. Feeding type communities

Among the four surveys in the Gulf of Mexico that emphasized feeding types, two noted deposit feeders (polychaetes) as dominant (Alexander et al., 1981; Weston et al., 1982), another indicated suspension feeders as dominant, at least in the Louisianna and Texas areas (Phillips and James, 1988), and yet another reported suspension feeders as dominant in the summer, shifting to deposit feeders in winter (Posey et al., 1998).

The East Coast also had relatively few surveys (six), which identified macrofauna to feeding types. Two surveys listed either carnivores and deposit feeders (Burlas et al., 2001), or carnivores and suspension feeders (Hobbs, 2000) as the dominant feeding types. One survey stated that deposit feeders were dominant in mud or silt sites (Applied Coastal Research and Engineering Inc., 2000). In contrast, it was reported that surface feeding polychaetes were dominant (Bowen and Marsh, 1988), or that location on the continental shelf, shelf-break, or slope determined dominant feeding types (Boesch, 1979). Only one study reported that filter feeders and surface deposit feeders increased, while subsurface deposit feeders declined, after sand-mining (Burlas et al., 2001). Overall, most surveys from both areas highlighted deposit or suspension feeders as the dominant feeding types.

3.5. Seasonality

Review of the 18 surveys that included information on seasonality of benthic fauna in the Gulf of Mexico indicated spring (Alexander et al., 1981; Berryhill, 1977; Blake, 1978; Blake et al., 1996; Byrnes et al., 1999; Fitzhugh, 1984; Harper, 1990; Phillips and Thompson, 1990; Shaw et al., 1982; Weston et al., 1982) and/or summer (Alexander et al., 1981; Blake, 1978; Blake et al., 1996; Environmental Science and Engineering Inc. et al., 1987; Saloman, 1974; Saloman et al., 1982; Vittor, 1978) as peak seasons for spawning, abundance, biomass, and diversity values. The focus of the surveys varied across taxa, with some studies relating seasonality to abundance of specific phyla, such as polychaetes (Fitzhugh, 1984; Vittor, 1978), molluscs (Blake, 1978; Phillips and Thompson, 1990) or arthropods (Heard, 1978), while others lumped infauna (Blake et al., 1996), meiofauna (Alexander et al., 1981; Phillips and James, 1988), or macrofauna (Culter, 1994a; Environmental Science and Engineering Inc. et al., 1987; Phillips and James, 1988) together. Of the three surveys examining the seasonality of overall macrofaunal abundance two studies indicated the summer (Environmental Science and Engineering Inc. et al., 1987), or warmer months (Phillips and James, 1988) supported higher densities, while the third stated that the winter months (Culter, 1994a) supported the greatest densities.

Late spring and summer were reported as seasons of highest abundance for macrofauna in several East Coast surveys. Three surveys identified late spring or early summer as months of peak abundance or density (Cutler and Diaz, 1998; Posey et al., 1998; Turbeville and Marsh, 1982). Alternatively, one survey reported highest abundances during a winter month (Dauer, 1980) and three reported higher densities in the fall compared to either summer (Boesch et al., 1977), summer and spring (Maurer et al., 1976), or spring (Byrnes et al.,

2003). In contrast, two surveys found a lack of seasonal trends in either megabenthos density (Boesch et al., 1977) or macrofaunal biomass (Maurer and Leathem, 1981). Taxon-specific patterns in seasonal abundance were common (Applied Coastal Research and Engineering Inc., 2000; Posey et al., 1998; Schaffner and Boesch, 1982).

3.6. Sand mining impacts and recovery

Seven papers from the Gulf of Mexico specifically addressed the impacts of dredging and/or sediment disposal on benthic fauna. Two studies found no change in infaunal density with dredging (Blake et al., 1996; Cutler, 1988), and five studies detected reduced densities in impact areas (Cutler and Mahadevan, 1982; Mahadevan et al., 1976; Phillips and James, 1988; Rice et al., 1981; Saloman, 1974). When infaunal species richness was considered, two studies found no change after dredging (Blake et al., 1996; Cutler, 1988), but four observed reduced infaunal species richness in the impact area (Cutler and Mahadevan, 1982; Mahadevan et al., 1976; Phillips and James, 1988; Saloman, 1974). Impacts

Table 3
Highlighted conclusion of studies which indicated recovery times post-dredging disturbance

Reference	Location	Study type	Conclusion
Boesch (1979)	East Coast	Survey/Experimental	Densities recovered in 43 weeks, but the resultant species composition was different.
Burlas et al. (2001)	East Coast	Survey	Overall, abundance, species richness, and taxonomic structure recovered within 1 year. Most taxa recover within 1 year with deep burrowers taking up to 3 years. Species composition will change in a mining area which is repetitively used.
Johnson and Nelson (1985)	East Coast	Survey	Densities and species diversity recovered in 9–12 months. The species composition was not identical within 1 year.
Jutte et al. (2002)	East Coast	Survey	Faunal densities were not significantly altered after 3–6 months. Species composition was still different after 30 months.
Mahadevan et al. (1976)	East Coast	Survey	Impact effects are not observed after 5–10 years.
Marsh et al. (1980)	Gulf of Mexico	Survey	A spill area recovered in terms of species diversity and species within 156 days. A dredged area had not recovered in density, biomass, species richness, or species composition within 45 days.
Posey and Alphin (2002)	East Coast	Survey	Infauna are similar 9–12 months post dredging. A few compositional changes remained post 1 year.
Ray (2001)	East Coast	Survey	Infaunal densities recovered by the next season with total recovery within 2–2.5 years.
Saloman (1974)	Gulf of Mexico	Survey	Abundance, species diversity, and mollusc size were all reduced within a sand mining pit three years post dredging.
Saloman et al. (1982)	Gulf of Mexico	Survey	Recovery after dredging takes 3–12 months for species richness and infaunal densities. Species composition was not identical after 1 year.
Turbeville and Marsh (1982)	East Coast	Survey	Infaunal density and species richness was greater in mined pits 5 years post dredging.
USPA (1983)	Gulf of Mexico	Review	Recovery from disposal is expected to occur within 7–12 months in shallow high energy areas.
Zajac and Whitlatch (2003)	East Coast	Experimental	Infaunal densities recovered within 3 months. Community structure recovered within 4 months.

did not appear to extend far from the dredged area (Lewis et al., 2001).

Within the East Coast, infaunal density (Collie et al., 1997; Ray, 2001) and species richness (Collie et al., 1997; Ray, 2001; Rowe, 1971) declined in areas impacted by dredging. However, three studies reported an increase in polychaete abundance post-dredging (Johnson and Nelson, 1985; Ray, 2001; Schaffner et al., 1996). One East Coast study found a higher density of infauna adjacent to an impact area (Rowe, 1971). In addition, one East Coast study found communities with a different species composition and higher productivity on swales versus ridges due to sediment differences as a result of dredging (Boesch et al., 1977). In summary, no consistent pattern of faunal response to dredging was found in the reviewed literature.

Thirteen surveys are available to provide estimates on the time period for recovery or recolonization of benthos in areas disturbed by sand mining (Table 3). Four of the studies were from the Gulf of Mexico and focused on dredging recovery. Two of the Gulf of Mexico studies showed that recovery takes place in less than 1 year (Mahadevan et al., 1976; Saloman et al., 1982; U.S. Ecological Protection Agency, 1983). Opportunistic polychaetes (U.S. Ecological Protection Agency, 1983; Vittor, 1978) and mobile crustaceans (U.S. Ecological Protection Agency, 1983), were shown to colonize disturbed areas first. The most rapid recovery times were recorded in a study of an accidental dredge material spill (recovery between 45 and 156 days; Mahadevan et al., 1976). In this study, the method of spill containment (i.e., whether the area is dredged for clean-up or left undredged) was found to affect species composition and density, with higher densities in the undredged area. Another survey, however, stated that complete recovery in terms of mollusc size frequency, species abundance, or species diversity was not observed three years post-dredging (Saloman, 1974).

Studies of recovery and/or recolonization time (Table 3) were more numerous on the East Coast with most studies showing recovery from 3 months to 2.5 years (Boesch, 1979; Johnson and Nelson, 1985; Jutte et al., 2002; Posey et al., 1998; Ray, 2001; Zajac and Whitlatch, 2003). Recovery of the original community composition has been suggested to potentially take a substantial amount of time to recover, especially in sand mining areas that are repetitively used (Byrnes et al., 1999). For example, deep burrowers may take up to 3 years to recover (Burlas et al., 2001). Two surveys followed faunal recovery over relatively long time periods (5–10 years), one indicating no long-term impacts present after 5–10 years (Marsh et al., 1980), and another showing increased faunal density and species richness in sand removal pits five years post-dredging (Turbeville and Marsh, 1982). As in the Gulf of Mexico, polychaetes and crustaceans recolonized impact areas more quickly than other taxa (Boesch, 1979; Bowen and Marsh, 1988). Molluscs, however, were slow to colonize impact areas (Bowen and Marsh, 1988).

4. Discussion

The majority of studies reviewed were surveys either conducted in relation to anthropogenic disturbance, or general assessments of benthos on the US East Coast and Gulf of Mexico. There has been a lack of survey work conducted in the western Gulf of Mexico and the southern East Coast. As was true for surveys, literature reviews were more frequent than experimental studies, but generally lacking from both the southern East Coast and western Gulf of Mexico. Thus, the western Gulf of Mexico and southern East Coast stand as areas in need of additional study. Only five experimental studies were found as a result of this literature search. The general lack of experimental work makes assessment of anthropogenic impacts tenuous at this time.

Most studies were conducted in a depth range of 200 m or less. Faunal relationships with depth varied widely, with no definitive associations identified. Several studies related species richness, abundance, and/or biomass to depth, but the studies arrived at various conclusions, making generalizations difficult. In general, most surveys spanned a wide range of depth strata. Studies over narrower depth ranges with greater replication would be beneficial for demarcating faunal relationships with depth, especially if fauna were identified to the species level, since associations may be species-specific.

Dominant taxa were reported across a range of taxonomic categories. While most studies listed dominant taxa to phyla or to the class level, several other surveys reported dominance to the family, genus, or species levels. A higher level of taxonomic resolution strengthens comparisons within and across regions, and allows for evaluations to be made between the Gulf of Mexico and East Coast,

as patterns of abundance for individual species may not mirror that of others and some species may be especially susceptible to anthropogenic impacts. Species-level analysis is also important to accurately assess trends in species richness. Thus the lack of species level analysis is a distinct deficiency for the offshore studies.

In common between the Gulf of Mexico and East Coast are several dominant polychaetes, Spionidae (i.e., *P. cristata*, *S. bombyx*) and Nephtyidae (*N. incisa*, *N. picta*), which are listed as mobile taxa. Spionidae polychaetes are tube-building surface deposit feeders while Nephtyidae are free-living predators consuming molluscs, crustaceans, and other polychaetes (Fauchald and Jumars, 1979). Surveys from the East Coast indicated a greater diversity of dominant taxa not reported for the Gulf of Mexico including, for example, filter-feeding polychaetes (Sabellidae and Sabellariidae), carnivorous polychaetes (Syllidae) (Fauchald and Jumars, 1979), tube-dwelling amphipods (*U. serrata* and *B. irrorata*) (Bousfield, 1973), and a bioturbating echinoderm (*E. parma*). The species composition of dominant taxa was found to be relatively similar in the north and south, with a few exceptions (e.g., *Prionospio*, polychaete). In the Gulf of Mexico, several polychaete species (*S. tentaculata, M. phyllisae*) were found to be predominant only west of the Missisippi River while the opposite pattern was true for dominant amphipod species. The amphipods, *Acanthohaustorius* and *Microdeutopus,* both free-living and tube-building genera (Bousfield, 1973), respectively, were common, but only east of the Mississippi River.

While the majority of surveys gave dominance information in terms of abundance, many either lacked dominance by biomass, or were inconsistent in parameters assessed. Many of the studies used wet weights instead of dry weights for biomass measurements, and several even measured mollusc biomass with shells included. Discrepancies in such measurements either make comparisons impossible, or strongly biased. Biomass estimates, however, are key components when estimating any type of energy budget for an area.

Among the literature examined, deposit and suspension feeders, as well as carnivores were all reported to be dominant in various studies. Increased information on feeding type is useful, as preliminary studies suggested that subsurface deposit feeders declined after anthropogenic disturbance. However, too few studies are currently available to evaluate trends. Such information could be easily gleaned from species-specific data or even if taxa were identified to specific families. For example, in the Gulf of Mexico, while mobile deposit feeding polychaetes dominated (e.g., *M. ambiseta*, *M. californiensis*, Spionidae) a diversity of polychaete feeding types was present including surface deposit feeders (e.g., *Tharyx marioni*, *M. stigera*), suspension feeders (e.g., Sabellidae, Sabellariidae), and carnivores (Nephtyidae, Lumbrineridae, Syllidae) (Fauchald and Jumars, 1979).

Based upon studies reviewed here, the strong animal–sediment relationships were not identified. Although numerous studies indicated in the methods that sediments were collected to describe the sedimentary habitat very little statistical analyses were performed to predict fauna distributions based upon sediment type. Most of the sediment analyses results were on a large-scale and results were inconsistent across studies. Inconsistencies among taxa were also apparent, at least in the Gulf of Mexico. Some studies indicated a lack of relationship, while others pointed to direct relationships, where fauna utilize specific sediment size category (shell hash, gravel, etc.). Additionally, sediment characteristics were not considered as important as temperature and salinity to meiofauna. In general, there is a clear need for improved study designs that include sampling strategies to examine relationships between fauna and abiotic features directly, including stratified designs, in order to enhance the rigor of statistical analyses used to examine such relationships.

Presently, it is difficult to draw conclusions about approximate recovery times from anthropogenic activities such as sand mining operations because of the paucity of studies. From the few studies available, it appears that general "recovery" of assemblages to background levels is within 3 months–2.5 years. However, this information is very specific to taxa, dredging operation, and environmental conditions, such as background disturbances, currents, etc. In most cases, polychaetes were the first to recolonize dredged or disposal sites, with crustaceans, specifically amphipods, also recolonizing relatively quickly. Some studies noted that carnivores recolonized dredged areas in a short amount of time, speculating that this response may be tied to the food resources available in dredged areas due to dead and injured organisms resulting from the dredging process itself. Measurements of recovery, however, were varied,

with some studies looking at general abundance of organisms, and others evaluating community structure. Those evaluating entire communities often indicated that while abundances of organisms may increase to background levels relatively quickly, community structure may remain altered for some time, and, in repetitively mined areas, may have difficulty ever recovering to the original state. Many studies reported that community structure differences still existed after 1 year. There were not enough studies to make any conclusions concerning recovery rates based upon differences in mining extent or intervals.

In summary, although there have been a number of benthic studies performed on the GOM and US East Coast continental shelf most studies were descriptive in nature with only 5% of the literature containing an experimental component. The literature survey revealed that polychaetes were the numerically dominant infauna on both the Atlantic and Gulf of Mexico continental shelf. Robust animal–sediment relationships were not readily detected from available studies mainly because of sampling design limiting statistical comparisons. Similar to animal-sediment associations, generalizations about fauna-depth relationships were difficult to construct due to differences in species-specific trends. From the limited studies on disturbance in GOM and US East Coast continental shelf, it appears that "recovery" by benthic assemblages from disturbance linked to sediment removal occurred within 3 months–2.5 years.

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