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The impact of shrimp trawling and associated sediment resuspension in mud dominated, shallow estuaries

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Abstract

To address the relative importance of shrimp trawling on seabed resuspension and bottom characteristics in shallow estuaries, a series of disturbance and monitoring experiments were conducted at a bay bottom mud site (2.5 m depth) in Galveston Bay, Texas in July 1998 and May 1999. Based on pre- and post-trawl sediment profiles of ^{7}Be; pore water dissolved oxygen and sulfide concentration; and bulk sediment properties, it was estimated that the trawl rig, including the net, trawl doors, and "tickler chain," excavate the seabed to a maximum depth of approximately 1.5 cm, with most areas displaying considerably less disturbance. Water column profile data in the turbid plume left by the trawl in these underconsolidated muds (85–90% porosity; <0.25 kPa undrained shear strength) demonstrate that suspended sediment inventories of up to 85–90 mg/cm^2 are produced immediately behind the trawl net; an order of magnitude higher than pre-trawl inventories and comparable to those observed during a 9–10 m/s wind event at the study site. Plume settling and dispersion caused suspended sediment inventories to return to pre-trawl values about 14 min after trawl passage in two separate experiments, indicating particles re-settle primarily as flocs before they can be widely dispersed by local currents. As a result of the passage of the trawl rig across the seabed, shear strength of the sediment surface showed no significant increase, suggesting that bed armoring is not taking place and the trawled areas will not show an increase in critical shear stress.

Keywords: sediments; shrimp trawling; sediment resuspension; seabed mixing; suspended sediment; galveston Bay; trinity Bay

1. Introduction

Galveston Bay supports a major shrimping and oyster harvesting industry, with a shrimping fleet of approximately 200 vessels. There have been a number of studies of the environmental impact of trawling on benthic community habitat (Gibbs et al., 1980; Van Dolah et al., 1991; Jones, 1992; Watling and Norse, 1998; Collie et al., 2000; Schratzberger et al., 2002), but little attention has been paid to the role shrimp trawling plays in resuspension of sediments. Quantitative evidence on the depth of penetration of a trawling net into bottom sediments over a range of bottom types is not readily available, but literature references suggest that it can vary from a few to 30 cm (Schubel et al., 1979; Jones, 1992, and references therein; Palanques et al., 2001). These studies suggest that the depth of penetration depends on the weight of the gear on the seabed, the towing speed, the nature of the bottom sediments, and the strength of bottom currents.

Qualitative observations of the impact of trawling on the seabed can be readily made using side scan sonar (Krost et al., 1990; Tuck et al., 1998; Palanques et al., 2001). Palanques et al. (2001) investigated the impact of offshore trawling on the muddy shelf off of Spain at a site in 30–40 m of water.

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The trawl gear was considerably larger than bay shrimping gear, with the offshore trawl doors weighing 750 kg each and a net opening of 30 m. They found that trawl marks could be observed by side scan sonar 2 years after they were created and that the trawl net scoured 2–3 cm of seabed, with the doors eroding much deeper. They also found that turbidity after the trawl remained elevated by a factor of three for 4–5 d after the trawl, and was composed of about 10% of the initial sediment inventory suspended by the trawl rig. Regional observations of turbid suspended sediment plumes on the mid-Atlantic Bight shelf were suggested to be linked to offshore trawling by rigs with openings up to 100 m wide (Churchill, 1989).

No comparable studies have been conducted on the impact of bay shrimp trawling, where substantially smaller shrimp trawling rigs are used and environments are shallow and vary on short spatial scales between sandy and muddy substrates. Within South Creek, a subtributary of the Croatan-Albemarle-Pamlico estuary, West et al. (2002) investigated the role of wind driven resuspension and trawling on the flux of nutrients in the water column. This study was focused on the water column rather than the seabed and found that shrimp trawling has a short-term impact on nutrient loading, but that the high rate of natural disturbance of wind-driven wave resuspension had a far greater affect on nutrient cycling than shrimp-trawling. Little mention of the impact on shrimp trawling on the seabed was given in this study.

Our study addresses the relative roles of shrimp trawling and wind driven wave resuspension in shallow estuarine systems. To address this issue, this paper focuses on the results of the physical impact of shrimp trawling on the seabed as determined from two shrimp trawling experiments at a bay bottom study site in Galveston Bay (Fig. 1).

Previous published work on this project by Warnken et al. (2003) used benthic flux chambers to investigate the fluxes of various chemical constituents across the sediment–water interface during pre- and post-trawl conditions.

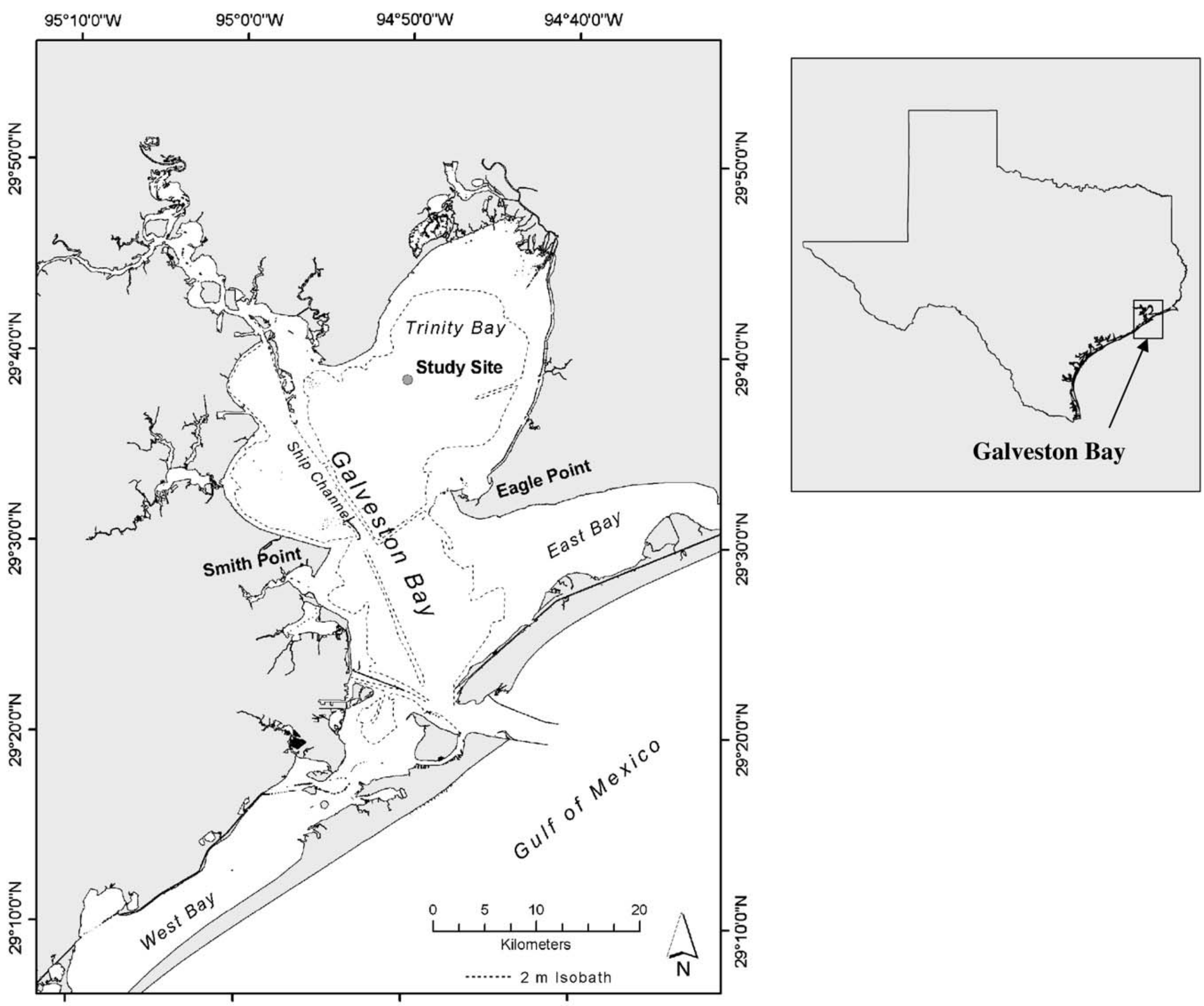

Fig. 1. Base map of study area showing the study site within Trinity Bay in the upper portion of Galveston Bay. Other than the Houston Ship Channel, Galveston Bay is generally a flat, shallow system with most areas less than 3 m deep.

2. Study area

2.1. Shrimping in Galveston Bay

The field experiments were conducted in Trinity Bay, which is the upper sub-estuary of Galveston Bay and includes the mouth of Trinity River. This shallow estuary (average bay bottom depth 3–4 m) supports a commercial industry that yields approximately 2.3 million kg of shrimp (white + brown) annually (Green et al., 1992). In recent years, the catch has been higher: 3.14 million kg in 1998, 2.8 million kg in 1999, and 3.3 million kg in 2000 (L. Robinson, personal communication). In 1989, the estuary produced 24–38% (by weight) of the Texas commercial harvest of shrimp, fin fish, crab, and oysters (Johns, 1990).

There are three different shrimping seasons in Galveston Bay specific to certain species or size classes: bait shrimp, white shrimp and brown shrimp. The bait shrimp season lasts all year and has a catch limit of 90.6 kg/day with the requirement that half of the catch must be kept alive for the live bait market. The shrimping day is from 30 min before sunrise until 14:00 h local time. The bait shrimping rig uses a minimum of a 3.53 cm mesh net, with a 9.7 m opening and 2.42 m long trawl doors. The brown shrimp season typically runs from May 5 until July 15, from 30 min before sunrise until 14:00 h local time, with a 273 kg catch limit. The net is much larger than the bait shrimp net, with an opening of 27.3 m, with a minimum mesh of 3.5 cm, more commonly 3.81 cm, and doors which are 2.4–2.7 m long. The white shrimp season typically runs from Aug. 15 to Oct. 31, from 30 min before sunrise to 30 min after sunset. There is no catch limit but the shrimp must be 110 count/kg or larger. The net has a mesh of 4.45 cm, otherwise the rig is the same as the brown shrimp season.

Shrimp catch is reported by subarea (Galveston Bay is Subarea 18) to the Texas Parks and Wildlife Department (TPWD) and the National Marine Fisheries Service (NMFS). Table 1 provides a summary of shrimp which was sold to seafood distributors for Galveston Bay for 1998–2001. Note that these numbers are for total shrimp, not broken down by species. Each trip reflects when a boat returns to the dock, while days fished is based on 24 hours of effort, which has been broken down into hours fished for the entire fleet.

2.2. Physical setting

Galveston Bay, with a surface area of ~1360 km^2, is the second largest estuarine system in Texas. The Trinity River accounts for approximately 90% of the freshwater input to Galveston Bay, which would be equal to an average discharge of 1547 m^3/s for the years 1954–1993 (SAGE, 2002). The river is also the single largest sediment source to Galveston Bay: in 2000 the sediment load was on the order of 4.24×10^9 kg/year (USGS, 2005). No published estimates are available for suspended sediment loads derived from marine exchange through barrier inlets at either end of Galveston Island. The present study is focused on Trinity Bay, which constitutes the northeastern portion of Galveston Bay. Ongoing maintenance dredging of the Houston Ship channel at the mouth of the Trinity sub-estuary, and other navigational channels probably provide a significant suspended sediment load (Ward and Armstrong, 1992; Ward, 1993). However, again, no figures are available.

Galveston Bay has an astronomical tide that is dominantly diurnal and has an average range of 39 cm during summer spring and 27 cm during summer neap tide. Predicted tidal currents average 0.82 m/s during neap tide and 1.4 m/s during spring tides (NOAA Predictions from Noble-tec Tides and Currents®). Galveston Bay is a shallow, microtidal, wind-dominated estuary and the primary source of bottom shear stress and water level fluctuation is meteorologically rather than tidally driven. Tropical cyclones, which hit somewhere along the Texas coast on an average once every 1.5 years (Byrne, 1975), provide the most energetic bottom stress. Other than tropical cyclones, the most energetic bottom shear stresses that generate seabed resuspension are associated with waves and direct wind stress during winter cold front passage in October–April. On the average, there are 46 cold fronts a year which pass through the Northern Gulf of Mexico (Henry, 1979). Cold fronts occur at 3–10 day intervals in a given year and are characterized by a pre-frontal phase of high-energy southeasterly winds for 1–2 days, followed by a 12–24 h period of strong northwesterly to northeasterly winds following passage of the front (Co-ops, 2005). Bottom pod-based experiments carried out during cold front events (Dellapenna et al., 2003) determined that a wind speed of 6 m/s out of the north is sufficient to generate significant resuspension in the bay bottom soft muds during these winter events. In 2000, there were 456 storm hours with winds out of the north which exceeded 6 m/s, resulting in an estimated total annual sediment resuspended inventory due to storm activity of approximately 1.79×10^{10} kg (Dellapenna et al., 2003). The Bay is also subject to a variety of anthropogenic mechanisms for sediment resuspension (e.g., shrimp trawling, oyster dredging, waves created by ships in the Houston Ship Channel).

Trinity Bay, with 3591 km^2 of bay bottom mud habitat in waters deeper than 1.5 m (~40% of the Bay area), was selected for the field experiments because it is the primary repository for fine-grained sediment in Galveston Bay (White et al., 1985), it is a major site for estuarine shrimping, and this habitat is probably the most common sedimentary environment in the shallow estuaries that characterize the US Gulf of Mexico region. Additionally, this habitat was selected because it represents a ‘‘worst case scenario’’ with

Table 1
Statistics on shrimp catch for 1998–2001 for Galveston Bay (Nance, personal communication)

Year	Trips	Pounds	Days fished	Days fished Trinity Bay
1998	32251	4492676	8802.08	2934.1
1999	32418	4161967	6647.63	2215.9
2000	37141	4655745	7526.92	2509.0
2001	30357	4056909	7690.21	2563.4

respect to volume of resuspension and the impact of shrimping on seabed habitat compared with other areas of the Bay, such as the sandy shallows, or the deeper bay inlet area of lower Bolivar Roads (which is also much sandier). Trinity Bay is also the repository for most of the riverine suspended sediment discharged by the Trinity River. The shrimping experiments were conducted during the summer period (May–August), when the wind energy tends to be the lowest, except when a tropical storm passes near the Bay (1.5 year average interval between storms; Byrne, 1975) to minimize the natural variability in "background" suspended sediment concentration.

Galveston Bay is also the home of the Houston-based petrochemical industry. The Houston Ship Channel extends approximately 50 km up the axis of Galveston Bay, where it enters the Port of Houston (Fig. 1). In 2002, the Port of Houston was ranked sixth in the world in terms of total metric tons of cargo, and number one in the United States, with 1.61×10^8 metric tons of cargo (McConville, 2004). Beginning in the latter half of the 20th century, the bay has experienced significant environmental impact due to both point source and non-point source discharges of pollutants such as trace metals and hydrocarbons (Morse et al., 1993; GBNEP, 1995). As a result, considerable harm to water quality and introduction of toxins into the estuarine food web potentially exists if materials stored in estuarine sediments are released by deep resuspension of Bay sediments (Valette-Silver et al., 1993).

3. Materials and methods

3.1. Field experiments

The bay shrimp boats, which were leased for the field experiments, carried standard gear and were active members of the Galveston Bay fleet. The M/V *Pisces* was used for the 1998 experiment and the M/V *JackyL* was used for the 1999 experiment. Both of these boats are ~10 m long and utilize a single trawl rig to catch shrimp. The first trawl experiment was conducted on 26–28 July 1998, with a second experiment of identical design on 5–6 May 1999. For each of the shrimp trawling experiments, the same basic trawling rig was used. As shown in Fig. 2, the rig consists of two, wood or metal trawl doors, each weighing in excess of 50 kg and measuring roughly 1.5 m × 2.5 m. Strung between the trawl doors are the trawl net and a tickler chain. The tickler chain drags along the bottom in advance of the net and is used to drive the shrimp out of the seabed. Typically, a 0.63 cm diameter link chain is used. Attached to the trawl is a Turtle Exclusionary Device (TED), which consists of two metal hoops and a metal grid, which are designed to shunt turtles out of the rear of the trawl net. A bay trawling rig typically weighs approximately 100 kg, the mouth of the net is 10 m wide and the net is 50 m long. For each experiment, the commercial shrimping boat was instructed to replicate their normal trawling procedures, which involved towing the trawl gear at approximately 2.5 kts (~1.25 m/s) through the study site.

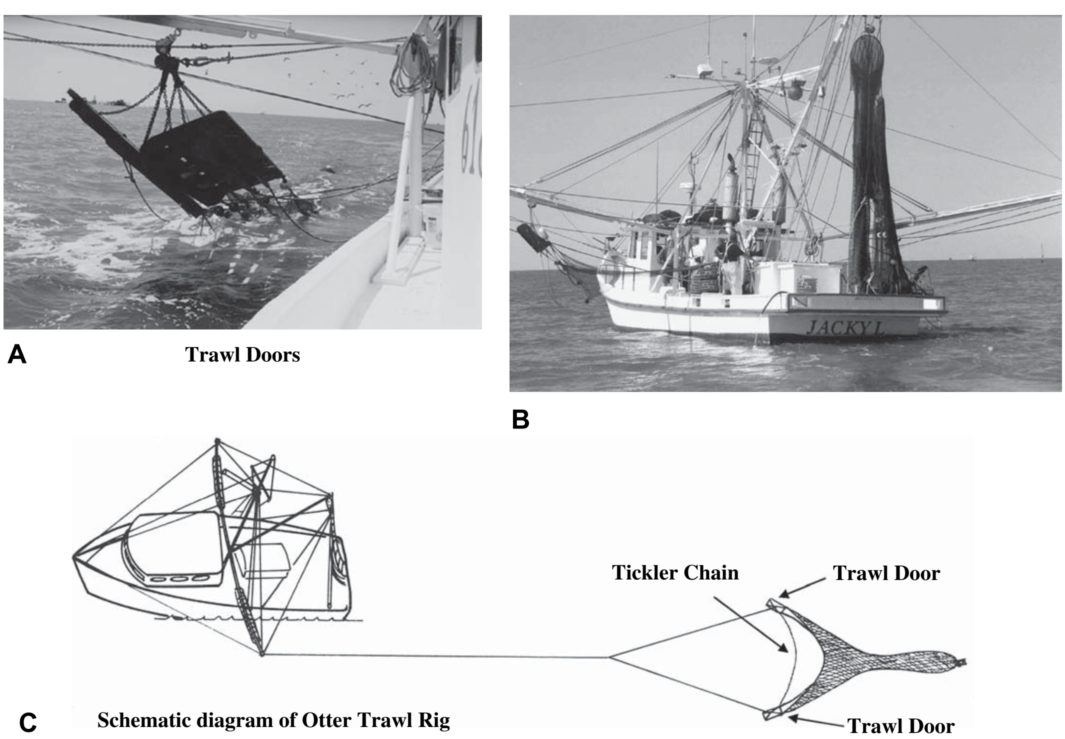

Fig. 2. Shrimp trawling rig, (A) with trawl doors of a bait trawling rig; (B) a suspended trawl net, the circular object at the top of the net is the turtle exclusionary device (TED). (C) The schematics of a typical trawling rig underway, showing all of the tickler chain and trawl doors.

For both the 1998 and 1999 experiments, a site was selected near the Trinity Bay mouth (Fig. 1) for the trawling tests. In each experiment, a 30 × 50 m study grid was marked out using surface buoys. Prior to the trawls, an InterOcean Systems™ S-4 electromagnetic current meter was deployed on a fixed bottom mooring 1 m off of the bed just outside the study grid. The S-4 current meter collects two horizontal axis of velocity measurements at right angles at frequencies up to 2 Hz, and utilizes a high-resolution pressure sensor to monitor changes in water level at tidal and wave frequencies. The current meter data collection extended throughout the duration (2 days) of the experiment.

Prior to the commencement of trawling, divers collected four sediment cores within the study grid, using 15 cm diameter PVC core tubes 60 cm long to examine pre-trawl stratigraphy. Two cores were analyzed immediately after collection for undrained shear strength of the sediment surface and two for dissolved oxygen profiles (see below). A Plexiglas rectangular subcore was then extracted from the shear strength cores for x-radiography and downcore shear strength profiles. These two cores were then extruded and subsampled at 0.5 cm depth intervals onboard a second (lab) vessel moored at the study site. Post trawl cores were collected within one half hour of the passage of the trawl, within 15 m of where the pre-trawl cores. Each time cores were collected, they were collected simultaneously using multiple divers. With each collection of the cores, the divers were only a few meters apart. Turbidity is very high in Galveston Bay and there is zero visibility for divers in the lower 1 m of the water column. In addition, at the time this experiment was conducted, we did not have access to a side scan sonar. The best we were able to do was collect our pre-trawl and post-trawl cores in the center of our site, in the middle of where the trawls had passed. Because there was zero visibility, there was no ability to specifically target cores sites on the bottom where there was a direct impact of trawl doors or tickler chain.

Following the pre-trawl data collection, the shrimp boat made three passes over the study grid in the same direction over a period of 30–40 min. Immediately (10 min) prior to the first passage of the trawler, a SeaBird™ Seacat19 CTD profiler with two SeaTech™ transmissometers (5 cm and 25 cm path length) and a Sea Point™ optical backscatterance sensor (OBS) was deployed in the study grid to determine water column properties (conductivity, temperature, depth, and suspended sediment concentration) from surface to seabed. A second CTD cast was made immediately after the first pass by following directly behind the trawler in a small boat. The small boat was then allowed to drift in response to local currents (and wind direction), to follow the resulting turbid water mass. CTD casts were taken at ~1 min intervals for approximately 20 min after the passage of the trawler. Two more passes were made with the trawl rig and within a half hour of the last passage of the trawl, divers were sent down to collect four more sediment cores within the area where the trawl had passed, within 15 m of where the pre-trawl cores were collected. These cores were processed onboard the second vessel to examine post-trawl conditions.

Subsequent to the shrimp trawling experiment, side scan sonar data were collected in November 2002 to examine the water column structure of the suspended sediment plume produced by the trawl rig and the resulting seabed features (trawl marks) produced by the rig. Data were collected by following with a second vessel, an actively working bait shrimp trawler, near the Trinity Bay study site. The side scan sonar images shown in this paper were generated with an Edgetech™ 272 tow fish working at 500 kHz and 100 m range. Data were recorded digitally and post-processed into mosaics using a CODA™ topside computer. Navigation was provided using a Trimble™ AgGPS 124/132 Differential GPS and position was corrected for layback. Acoustic images were contrast stretched and brightness inverted so that higher backscatter intensity is portrayed as white.

3.2. Laboratory analyses

Activities of the particle-reactive radiotracer ^{7}Be were measured using a Canberra™ semi-planar, intrinsic germanium detector, coupled with a multichannel analyzer. Samples were homogenized, packed wet, sealed into 70 ml Petri dishes, and counted for ~24 h. Samples were then dried at 60 °C to determine weight analyzed. Activities were measured using net counts under the gamma peaks at 477 keV. Net count rates were converted to activities using detector efficiencies with sediment standards at the specific gamma-ray energies. Identical geometries were used for all samples. Deposition rates were calculated using the model of constant initial concentration (CIC; Robbins and Herce, 1993). The CIC model assumes a constant ratio between the delivery rate of the isotope and the deposition rate, thus a "constant initial concentration" of material. Because Trinity Bay has an average depth of less than 3 m and because the water column experiences a great deal of vertical as well as lateral mixing, it was assumed that, in regards to the half life of ^{7}Be, the assumption of constant initial concentration was met.

Water content and porosity measurements are used in the calculations of radioisotope activities. Samples for water content and porosity were collected when cores were subsampled for radioisotope analyses. About 30 ml of homogenized mud sampled from the cores were placed in pre-weighed centrifuge tubes which were capped and brought back to the lab. The wet samples were weighed, oven dried at 60 °C for a minimum of 7 days, and re-weighed to determine water content. Estimates of salt content and particle density were used to calculate porosity (Dellapenna et al., 1998).

Select samples were examined for grain size in order to determine if trawling has any selective winnowing effect on the seabed. Sediment sample aliquots were wet-sieved to separate the coarse fraction (>62.5 μm) which was then dried and weighed. The percentage of clay (<4 μm) and silt was determined by pipette analysis following the methods outlined by Folk (1980). Undrained shear strength was also determined for the cores using a fall cone penetrometer. Immediately after collection of the PVC cores, they were opened and drained of overlying water with a siphon. Replicate (3–5 each core) fall cone tests were made on each of the eight core sediment surfaces.

Subcores were then taken and x-rayed with a Kramex PN-20 portable unit operating at 15 keV/70 ma. These subcores were then opened by removing the fourth side and fall cone tests were made at 1 cm intervals downcore. Fall cone values were converted to undrained shear strength using the methods of Lunne et al. (1997).

Microelectrode probes were used to collect dissolved oxygen and sulfide profiles from the sediment cores within 1 h of sampling as another method of determining depth of reworking by the trawl. Precision Measurement Engineering oxygen and sulfide microelectrodes were used, each with a tip diameter of approximately 6 μm (Revsbech, 1989). Cores were placed on a laboratory jack, and were raised at millimeter increments, allowed to equilibrate, and the voltages were recorded to determine porewater concentrations of the relevant constituents. For reference, samples of the overlying water column were collected in capped syringes by divers swimming up-current in the bottom waters in close proximity to the core collection sites.

Suspended sediment concentrations versus voltage curves were determined for the transmissometer and OBS results from the CTD profiler using a suspended sediment water bath. Water and surface sediments from the study site were used for the calibration. Total suspended sediment inventory was determined by integrating the suspended sediment concentrations for each depth profile.

4. Results

4.1. Site characteristics and coring results

Both pre-trawl surface sediments from cores at the study site show a nearly uniform grain size distribution, averaging 3.5% sand and 96.5% mud with a mean grain size of the mud fraction for all of the samples of 7.5 phi (5.5 μm). Undrained shear strength of pre-trawl cores were 0.18 and 0.15 kPa and post-trawl cores were 0.14 and 0.09 kPa. Fall cone penetrometer measurements were conducted on the sediment surface of the four cores in 1998 and showed no difference between pre-trawl (0.08 and 0.11 kPa) and post-trawl (0.09 and 0.09 kPa) in undrained shear strength. Downcore measurements conducted on subcores indicate there was a ~5 cm thick surface zone of relatively low shear strength (<0.25 kPa) in all the cores, with no significant differences between pre- and post-trawl sites.

X-radiographs were collected from the trawl site. Although the exposures of these x-radiographs were too long and they developed too dark to be reproduced for publication, they reveal intense bioturbation for the upper 20 cm of the cores, with abundant preservation of small burrows and no preservation of primary laminations. This indicates that the sediment mixing resulting from this bioturbation was intense.

Sediment profiles of total ^{7}Be were prepared (Fig. 3) for pre-trawl cores collected in the 1998 experiment. The maximum depth of ^{7}Be was found to be in the 1.5–2 cm interval for Core 11 and the 2.5–3.0 cm interval for Core 12 (Fig. 3). Since ^{7}Be has a half life of 53 days and the x-radiographs reveal intense bioturbation at the study site, the deep penetration of ^{7}Be likely results from both bioturbation and possibly from short-term sediment deposition. However, separating these two factors is not possible with the available data. The ^{7}Be profiles do not show any clear trends between the pre- and post-trawl cores.

The primary application of the micro-electrode probes for this paper was to determine the depth of the redox potential discontinuity (RPD) for pre- and post- trawl conditions for specific redox constituents (see Warnken et al., 2003 for

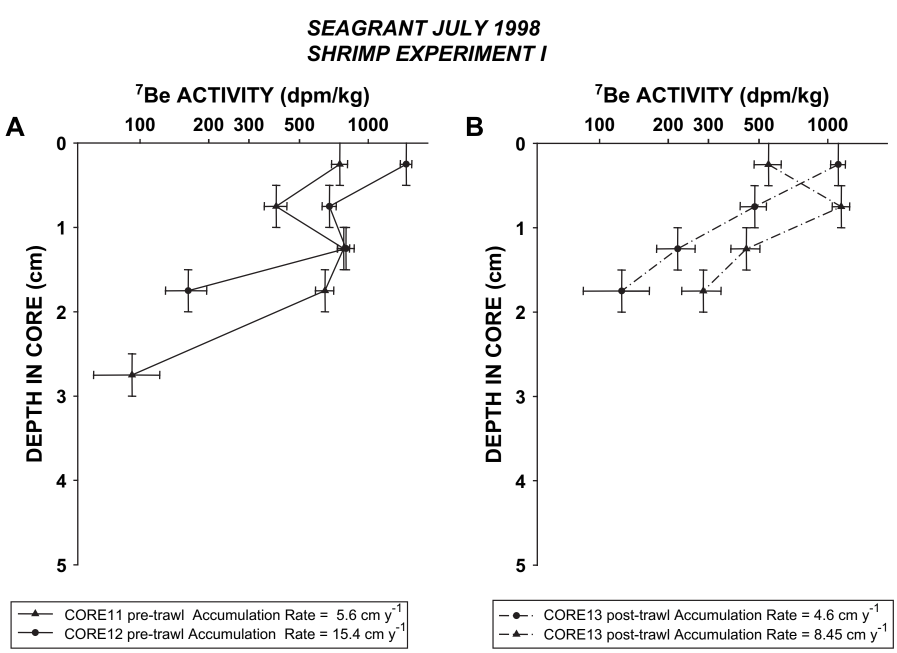

Fig. 3. ^{7}Be profiles of cores collected during both pre- and post-trawl conditions. In all cases, ^{7}Be reached background levels above a depth of 3 cm.

further application). In each of these profiles, the relative shift from high potential to low potential represents a depletion of the constituent of interest and where this change occurs represents the RPD for the relevant electron acceptor. In the 1998 experiment, the dissolved oxygen (DO) profiles for two pre-trawl cores were found to have a RPD at 1.25 and 1.9 cm (Fig. 4A) and for the post-trawl the RPD occurred at 0.5 and 1.5 cm. There were three pre-trawl and three post-trawl cores profiled for the 1999 experiment (Fig. 5A). No DO penetration was observed in any of these cores, so the RPD for the sulfide profiles were used. Note that the horizontal axis for sulfide is a negative scale. In the 1999 cores, the sediment–water interface was preserved, as a result, the core profiles begin at −1.0 cm, which is in the water column. The zero depth is the sediment–water interface. For the pre-trawl cores, the RPD was found at depths ranging from 1.3 to 1.8 cm depth, while the post-trawl RPD was 0.1, 0.3, and 1.4 cm respectively.

4.2. Water column turbidity

Transmissometer casts were made from a small boat during pre-trawl conditions, at 5 min after the trawl passage and at 11 min after the trawl passage for the 1999 Experiment (Fig. 6). During pre-trawl conditions, the suspended sediment concentrations were nearly uniform at ~10 mg/l throughout upper 2.5 m of the water column and ~25 mg/l in the near-bottom (0–0.5 m). Immediately following trawl passage, the water column suspended sediment profile was highly irregular before becoming homogenized vertically at approximately 5 min after trawl passage. At that time, suspended sediment concentrations throughout the water column in both experiments reached concentrations of approximately 225 mg/l at the surface and 350 mg/l near the seabed. At 11 min after the passage of the trawl, concentrations in the upper 1 m of the water column had returned to near pre-trawl levels, but the lower 1.5 m of the seabed continued to have elevated suspended sediment concentrations (up to 180 mg/l). This decrease in sediment concentrations is also shown in Fig. 7 as change in total (depth integrated) suspended inventory after the passage of the trawl rig. For the 1998 experiment, total suspended sediment inventory peaked at 88 mg/cm^2 and remained elevated for the first 4 min before declining to background levels at about 14 min after trawl passage. During the 1999 experiment, peak total suspended sediment inventory was not reached until 5 min after the passage of the trawl at 85 mg/cm^2, and, again, returned to background levels after about 14 min.

In November 2002, during the bay shrimping season, side scan sonar transects were conducted at the Trinity Bay study site and in other portions of Galveston Bay, where active shrimping was being conducted. Fig. 8 shows an image of an actively working bay shrimp trawling rig, as well as the sediment plume which was generated due to the rig. This image was collected in the Galveston Bay ship channel (10 m water depth), in similar bottom sediments to the study site, by orienting the side scan survey vessel on a reciprocal course to the trawling vessel.

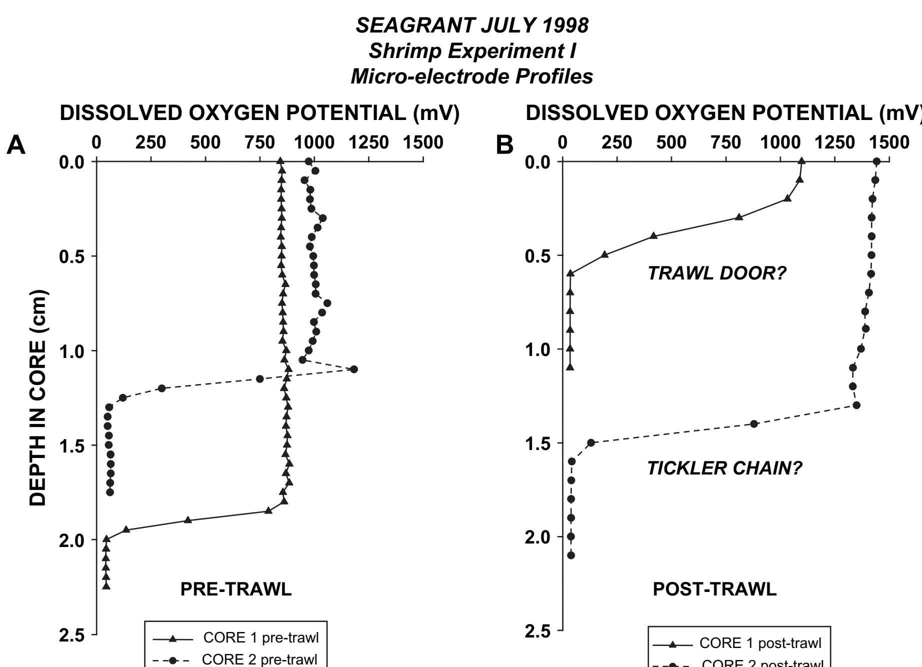

Fig. 4. Dissolved oxygen potential: July 1998 cores showing the pre- and post-trawl conditions. The abrupt shift in the profiles represents the redox potential discontinuity (RPD) and it is the relative change in depth of the RPD which was used to assess difference in the disturbance depth between pre- and post-trawl cores. Note that although there appears to be at least 0.5 cm of spatial heterogeneity between the depth of the RPD. Between the pre- and post-trawl cores there is a three-fold increase in spatial heterogeneity. This increase in spatial heterogeneity in the two post-trawl cores probably reflects the impact of different parts of the trawl rig. One suggestion is that the trawl door removed more surface sediment than the tickler chain.

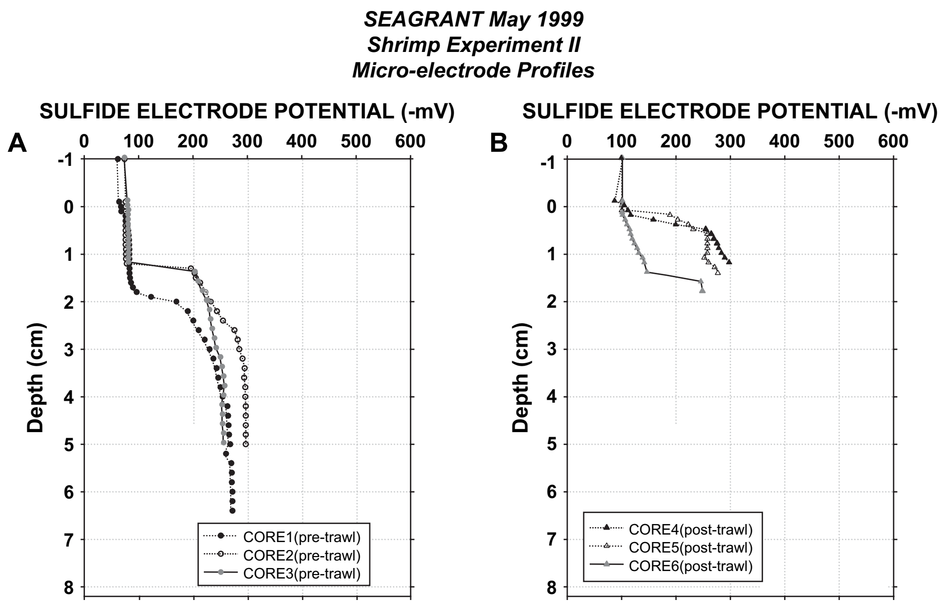

Fig. 5. Sulfide electrode potential: May 1999 cores. There was no dissolved oxygen at the surface during the May 1999 experiment. The abrupt shift in Eh of these profiles represents the redox potential discontinuity (RPD). Pre-trawl cores consistently have an RPD which is 1–2 cm deeper than the post-trawl cores, with a three-fold increase in the spatial heterogeneity. This shallowing of the RPD in the post-trawl cores may be the result 1–2 cm of sediment having been removed in the post-trawl cores compared with the pre-trawl cores.

5. Discussion

5.1. Estimations of excavation depth

The results of both trawl experiments show that there are significant impacts to the seabed and the water column due to the passage of a Bay trawling rig being dragged across the seabed under normal operations. Of the variety of techniques used to determine the depth of disturbance into the seabed due to the passage of the trawl rig, the microelectrode probes gave the most resolution in the estimates. There is a 0.5–0.75 cm difference in the depth of the RPD in the five pre-trawl cores collected between the 1998 and 1999 experiments (Figs. 4 and 5) and these differences appear to result from small-scale spatial heterogeneity of the RPD depth on the order of 0.5 cm. This small scale spatial heterogeneity likely results from variations in diffusivity of relevant chemical constituents, bioturbation and other physical disturbances. There are differences in the depth of the RPD in the five post-trawl cores of 0.25 and 1.7 cm. These variations in the depth of the RPD suggest a three-fold increase in the spatial heterogeneity of the RPD depth between the pre-trawl and post-trawl cores. This increase in spatial heterogeneity in RPD depths for the post-trawl cores probably reflect a combination of both pre-trawl spatial heterogeneity and real differences in the thickness of sediment removed or disturbed by the trawl rig (Figs. 4 and 5). Although there were only three cores collected for the post-trawl cores, the three-fold increase in the spatial heterogeneity of the depth of the RPD suggests that there have been real changes to the depth of the RPD in the post-trawl cores. It appears that the sample interval (0.5 cm) for ^{7}Be data was too coarse to resolve these differences.

The side scan sonar image of the trawl rig deployed in Galveston Bay (Fig. 8) shows that the majority of the suspended sediment plume appears to be produced by the two trawl doors dragging along the bottom. Note that there are abundant trawl door marks in the image as well, which were produced by previous passes of similar shrimp trawling rigs. These marks are the product of acoustic shadows produced by the erosional depressions excavated by the dragging of the doors. Similar trawl marks were observed in the vicinity of the Trinity Bay study site in November 2002. The furrows and sediment plumes observed following trawl passage in side scan sonar images (Fig. 8) suggest that sediment removal appears to be primarily by the dragging of the trawl door along the seabed while the area under the tickler chain is likely subjected to significantly less impact. The deeper removal by the trawl doors may also explain why the RPD was up to 1.5 cm shallower in the post-trawl cores than in the pre-trawl cores. The overall three-fold increase in spatial heterogeneity of the depth of the RPD in the post-trawl probably reflects varying impacts to different portions of the trawl footprint. This effect is magnified by the integration of three trawl passes before the cores were taken. Although there was no attempt to exactly reproduce the track in each of the three passes, the trawl door impact area is likely limited to a subset of the study site. Given the multiple passes involved, the differences in the spatial heterogeneity of the RPD in the post-trawl cores suggests that the depth of trawling removal (the door zone) in a single pass is about 1.5 cm.

An independent estimation of the erosion depth due to the trawl can be made using the suspended sediment concentrations from the trawl plume. The first passage of the trawl rig resulted in suspended sediment concentrations being elevated by at least an order of magnitude throughout the entire water column for at least 5 min. The maximum concentrations

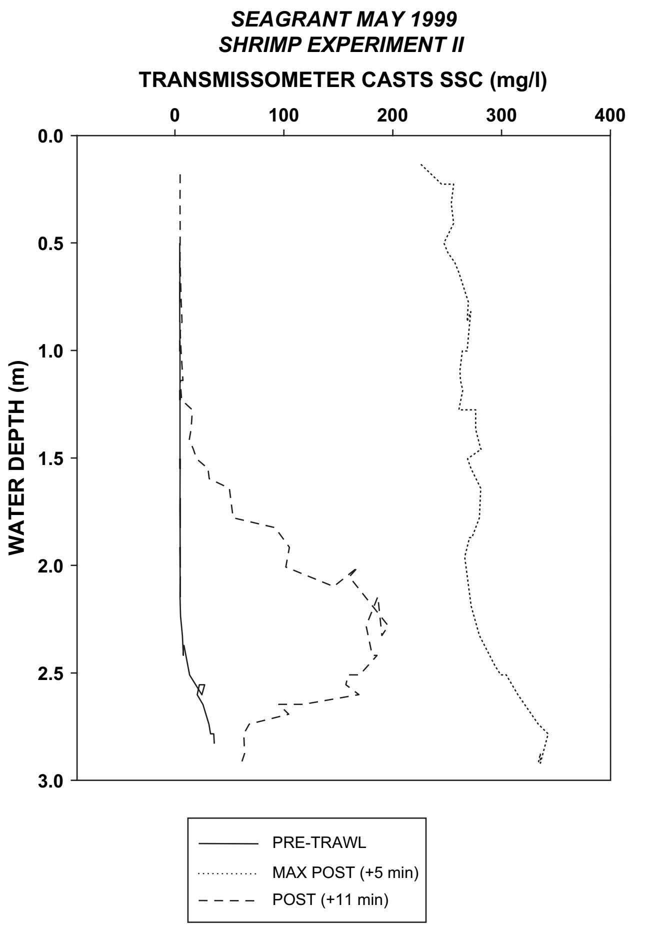

Fig. 6. Suspended sediment profiles of the water column for pre-trawl conditions, 5 min after trawl passage and 11 min after trawl passage for 1998 and 1999 trawl experiments, as determined from transmissometers. Note that the suspended sediment concentration in the pre-trawl profile is consistently low except for the bottom 0.5 m which represents the benthic boundary layer of high turbidity. Five minutes after the trawl the profile shows a nearly uniform profile of high turbidity and 11 min after the trawl, much of the turbidity has settled to the lower meter of the water column.

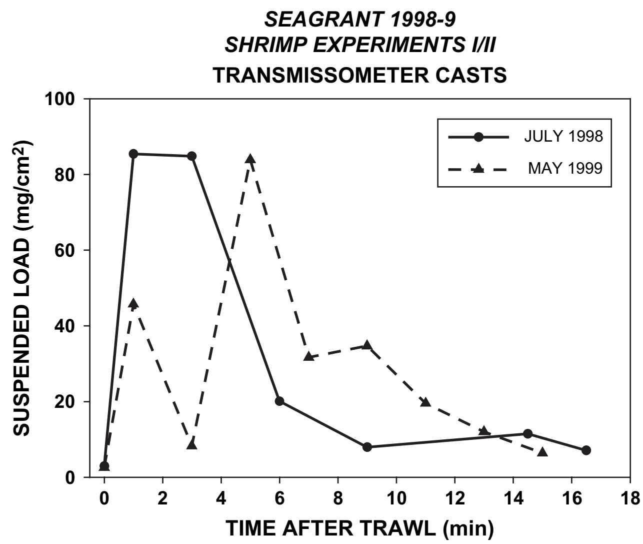

Fig. 7. Suspended sediment inventory versus time after trawling. Note that in both experiments the suspended sediment load had largely settled after 7 min and had reached nearly background levels by 15 min after the passage of the trawl rig.

observed in the water column equates to a maximum sediment inventory of 88 mg/cm^2. If we assume the surface porosity is 86%, which was the surface value determined while measuring porosity as part of the ^{7}Be measurements, and we use the observed maximum total suspended inventory found within the study site, then the observed suspended sediment inventory would equate to a net trawl incision depth of about 0.24 cm. If we assume the impact is made strictly by the doors (2 doors × 1.5 m wide and dragged at a 45° angle) then the surface area impacted by the trawl is reduced to 15% of the original area and the incision depth is increased to 1.6 cm. This estimate assumes all resuspension is due to the trawl doors and assumes a constant incision depth and no suspension due to the tickler chain. These assumptions are likely not entirely met, the tickler chain probably dragged in places, the trawl door dug in deeper in some places and less in others, the net may have also dragged along the bottom in places, all adding to variations in suspended sediment yield. This assumption also assumes that all of the sediment is suspended rather than plowed out of the way. However, this estimation based on suspended sediment yield provides a result which is comparable to the estimates of the depth of incision based on the core data (1.5 cm), suggesting that our estimates of incision depth based on core data are reasonable.

5.2. Relative impact of shrimping on resuspension in Galveston Bay

The observations outlined above suggest that the size and weight of the trawl doors, as well as the rigging of the trawl doors, are the key factors in seabed disturbance by estuarine shrimp trawling rigs. The trawl experiments were conducted using a bait shrimping rig, the brown shrimp rig utilized in Galveston Bay has trawl doors 10% wider and at least 10% heavier. Presumably the impact on the seabed by these rigs would be even greater than the impacts observed in this study. Changes in bottom sediment type are also likely to change the degree of seabed disturbance and resuspension volume. For example, for a sandy substrate, a similar incision depth will result in a much lower concentration suspended sediment in the plume because there is less mud in the sediment being scoured. However, the impact on the benthic community could be greater because macroalgae are generally found only within the sandier substrates, and they also support a more diverse benthic community in Galveston Bay and other shallow Gulf estuaries (Medlin, 1984). Because a greater volume of fine particles and their particle-reactive contaminants are resuspended, and the fact that larger volumes of pore water (and dissolved compounds) will be released in high porosity bay bottom muds, the impact of trawling on the water quality in muddy substrates will be much greater. During the trawl experiments it took 14 min for the water column to return to normal after the passage of the trawl. Although some of the plume

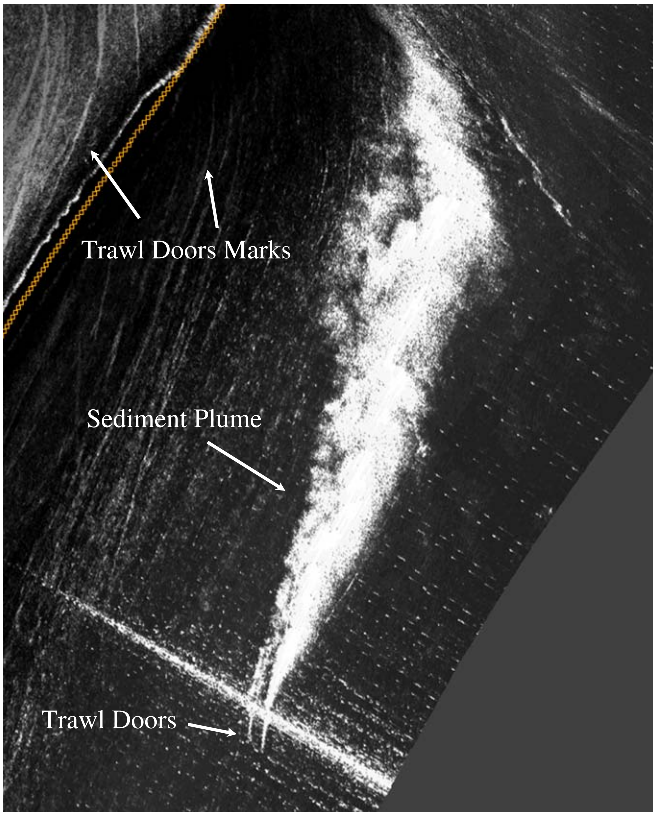

Fig. 8. An active shrimp trawling rig in the Galveston ship channel imaged by side scan sonar. Note that the trawl doors produce the majority of the suspended sediment plume. The image also shows how the plume rapidly expands after the passage of the trawl rig. Most of the light lineations in the image are older trawl door marks.

likely was advected away, the turbidity profiles show that 11 min after the passage of the trawl, there was still a high suspended sediment concentration in the lower 1 m of the water column. This suggests that much of the suspended sediment settles back down as flocs rather than being widely distributed by local currents.

Using benthic flux chambers deployed pre- and post trawl at the Trinity Bay study site, Warnken et al. (2003) found enhanced flux rates of ammonium and manganese out of the seabed for post-trawl conditions. These are both microbially mediated redox constituents. By removing the surface sediment layer with the passage of the trawl, it appears that fluxes in these muddy sediments can also be enhanced by excavating the seabed so that the sediment-water interface is closer to where these constituents are generated in the seabed.

By using NMFS reports (Nance, personal communication) of the number of days fished in the Trinity Bay subestuary (Table 1), and assuming that for each day fished, the shrimper worked 6 h, towing the net at 1.25 m/s and using only the bait shrimping rig, first-order estimates of the total annual release of suspended sediment by shrimp trawling can be made for Trinity Bay. Table 2 shows the results of these estimates, the area of impact is assumed to be the area of two bay shrimping trawl doors (3 m wide) and the values used for the Trinity River sediment load are from USGS measurements in 1977–1981 (USGS, 2005). Based on these assumptions, an area of 492 km^2, which is equivalent to the entire bay bottom for Trinity Bay, is trawled on an annual basis and as much as 30% of this area may be impacted by trawl doors. If it is assumed that the trawl doors erode 1.5 cm of sediment, then the suspended sediment load produced by shrimping in Trinity Bay ranges from 8.5 to 11.3×10^9 kg/year, which is equivalent to 202–267% of the estimated average suspended sediment supplied by the Trinity River, which itself constitutes over 90% of the fluvial input to the entire Galveston Bay system (SAGE, 2002).

The impact of natural processes such as the passage of meteorological fronts, may volumetrically resuspend orders of magnitude more sediment integrated over a year in comparison with shrimp trawling (Dellapenna et al., 2003). However, each frontal event will probably resuspend only a few millimeters of surface sediment, releasing an order of magnitude less sediment, and a far smaller volume of pore-water and particle bound chemical constituents per unit area than the passage of a shrimp trawl. Most meteorologically driven sediment resuspension occurs during the passage of northern fronts which mainly occur during the winter months (Henry, 1979; Hardy and Henderson, 2003). Based on annual variations in chlorophyll-a (Örnólfsdóttir, 2002; Pearl et al., 2003), primary production is at its highest November through March. As a result, the total amount of sediment resuspended in the winter months due to the passage of the meteorological fronts is higher and the impact on the biological community may also be higher. Shrimp harvesting is at its peak intensity during the summer months, when primary productivity in the bay is lower. Consequently, the impact of the resuspension of sediment and the release, uptake and bioaccumulation of contaminants, as well as the utilization of organic matter and nutrients

Table 2
Comparison of suspended sediment generated by shrimp trawling and suspended sediment inventory and load from Trinity River

Year	Distance fished at 1.25 m/s (km)	Total trawl area at 10 m net opening (km^2)	% of Trinity Bay bottom[a]	Area of trawl door impact at 3 m width (km^2)	Volume of seabed impacted at 1.5 cm depth (m^3)	Sediment inventory yielded (kg)	% Trinity River sediment load (%)[b]
1998	4.75E+05	4.75E+03	132.4	142.6	2.14E+07	1.13E+10	267
1999	3.59E+05	3.59E+03	99.9	107.7	1.62E+07	8.56E+09	202
2000	4.06E+05	4.06E+03	113.2	121.9	1.83E+07	9.69E+09	229
2001	4.15E+05	4.15E+03	115.6	124.6	1.87E+07	9.9E+09	234

[a] Based on an area of 3592 km^2.
[b] Based on sediment load average for 1977–1981, the only data available.

released from the seabed, may actually have a lower impact due to the elevated summertime shrimping activity than there would in the winter. As a result, sediment resuspension due to the passage of winter fronts probably has a greater impact on bay ecosystem health than does the sediment resuspension due to shrimp trawling. However, the physical impact of the benthic community may be greater due to shrimp trawling because the excavation depths are much greater and will likely impact larger, longer living organisms than does wind driven sediment resuspension.

6. Conclusions

A variety of techniques were used to determine the character and depth of disturbance and the amount of sediment resuspension caused by shrimp trawl rigs in Galveston Bay. The most effective technique for determining depth of disturbance was the use of sulfide and dissolved oxygen micro-electrode probes to examine the changes in the RPD between the pre- and post-trawl cores. The small scale spatial heterogeneity of the depth of the RPD increased by three-fold in the post-trawl cores. Based on these differences in spatial heterogeneity, it appears that the passage of the trawl eroded the seabed on average, about 1.5 cm. Side scan sonar observations show that the major impact by the shrimp trawling rig is produced by trawl door incision. In addition to the trawl marks left behind by door passage, the side scan images also show the suspended sediment plume primarily originates from the area where trawl doors are being dragged across the seabed. For bait shrimping rigs used for the experiments, the trawl doors comprise 15–30% of the width of the trawl rig track.

Measurements of suspended sediment within the sediment plume after the passage of the trawl rig show that 5 min after the passage of the trawl, suspended sediment was distributed nearly uniformly throughout the water column at an average concentration of ~250 mg/l and total suspended sediment inventories reached 88 mg/cm^2. Based on the number of days reported by NMFS for shrimping in Galveston Bay, it was estimated that for Trinity Bay, on average an area equivalent to at least 100% of the Bay bottom is trawled annually and 30% of that area is impacted by trawl doors. It was further estimated that the suspended sediment load created by shrimp trawling was equivalent to 200–267% of the suspended sediment being derived from the Trinity River.

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