BENTHIC RESPIRATION AND NITROGEN RELEASE IN BUZZARDS BAY, MASSACHUSETTS

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by

Gary T. Banta¹, Anne E. Giblin², John E. Hobbie², and Jane Tucker²

¹Boston University Marine Program, Marine Biological Laboratory, Woods Hole, Massachusetts

²The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts

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EXECUTIVE SUMMARY

The continuing eutrophication of coastal waters, and the associated loss of resources and habitat, is a primary concern of government agencies, scientists, and citizens alike. The result is higher levels of primary production, changes in algal species assemblages, depletion of bottom water oxygen concentration, destruction of benthic habitat and other problems. The ultimate cause of eutrophication is increased nutrient loadings, especially of nitrogen, to coastal waters from the population centers and anthropogenic activities located in the watersheds surrounding these coastal regions.

The sediments of coastal environments play a significant role in the nutrient cycling and eutrophication of these enriched coastal waters. A substantial portion of the organic matter produced in coastal waters is deposited on the sediments where it is decomposed and most of the nitrogen contained in the organic matter is cycled back to the overlying water. As a result, much of the nitrogen entering coastal environments is regenerated from the sediments and may be recycled several times between the water column and the sediments before it is lost from the system; this recycling helps sustain, in part, the high algal productivities of coastal areas.

The overall goal of this study was to address the degree of eutrophication of Buzzards Bay as it is reflected in sediment biological processes and benthic biota. This overall goal was accomplished by: 1) measuring benthic respiration and nitrogen release rates from the sediments of Buzzards Bay; 2) assessing the importance of factors, such as benthic animal abundances and sediment carbon and nitrogen content, that control these benthic processes; and 3) determining whether macrofaunal abundances in Buzzards Bay have changed since the Sanders' studies during the 1950's.

We found that benthic flux rates, especially benthic respiration, in Buzzards Bay are somewhat lower than those of similar coastal environments such as Long Island Sound and Narragansett Bay. Also, relative to these other areas, Buzzards Bay appears to be more efficient at recycling the nitrogen that is deposited on the sediments back to the overlying water (i.e., Buzzards Bay loses less nitrogen through denitrification than these other environments).

The factors which we found to be best correlated with the rates of benthic fluxes in Buzzards Bay were water temperature and sediment chlorophyll <u>a</u> concentration. We believe the latter parameter is a good surrogate measure of organic matter loading rates to the sediments. Sedimentary carbon or nitrogen content and macrofaunal abundances were not useful for predicting benthic fluxes. Our results suggest that any model predicting benthic flux rates in Buzzards Bay based on annual temperature cycles would be greatly improved if it also incorporates a parameter, such as sedimentary pigment concentration or sedimentation rate, that reflects the flux of algal detritus to the sediments.

Benthic animal densities reported in this study are significantly higher than estimates made for Buzzards Bay in the 1950's; however, due to differences in animal collection and sorting techniques between the earlier studies and this work, it is difficult to say whether there has in fact been an increase in animal abundances in Buzzards Bay or whether there is simply a methodological bias. In either case, there appears to have been little change in the structure of the benthic animal community in Buzzards Bay during the past thirty years except for the possible increase in relative abundance of small polychaetes such as <u>Mediomastus ambiseta</u>. This is in contrast to more drastic changes in both macrofaunal abundances and community structure seen in Long Island Sound and Narragansett Bay.

All of these observations taken together suggest that Buzzards Bay is currently less eutrophied than many other coastal environments such as Long Island Sound and Narragansett Bay.

INTRODUCTION

The primary production of coastal marine waters and the lower reaches of most estuaries is limited by the availability of nitrogen. Studies have shown that in all but a few locations the input of "new" nitrogen from runoff, precipitation, and fixation is insufficient to support the observed rates of primary production (Dugdale & Goering 1967; Harrison & Hobbie 1974; Nixon 1981; Kemp et al. 1982). The remainder of the nitrogen required to support primary production must be supplied by the <u>in situ</u> regeneration of nutrients from the benthos and within the water column (see Nixon & Pilson 1983). It is important to understand the relative contributions of "new" vs. recycled nitrogen in order to understand the nutrient dynamics of coastal environments.

In coastal waters much of the nitrogen needed to support primary production is recycled back to the water from organic matter degradation occurring within the sediments (Nixon 1981). In open ocean waters, in contrast, it is estimated that 82-87% of the nitrogen necessary to support primary production is regenerated as ammonium within the water column from the breakdown of organic matter produced in the overlying waters (Epply and Peterson 1979). The amount of recycling within the water column increases to as high as 94% within subtropical gyres (Epply and Peterson 1979).

However, the role of the benthos for regenerating nutrients in different coastal areas is quite variable, supplying anywhere from 0% to more than 100% of the nitrogen needed for primary production (Nixon 1981). This variability is part of the reason that there is not a very "tight" relationship between nitrogen loadings to coastal areas and primary production in the nearby coastal waters. It is true that in general, coastal environments with higher nitrogen loadings exhibit higher rates of primary production (Nixon & Pilson 1983; Boynton et al. 1982). However, when different systems are compared (Nixon & Pilson 1983; Boynton et al. 1982), a wide range of primary production rates are observed for any given level of nitrogen loading. Although differences in the flushing times of coastal embayments may explain some of the variation in this relationship between nitrogen loadings and primary production, a large part is due to differences in benthic regeneration.

The complexity of the relationship between nutrient loading and benthic recycling is illustrated by the experimental addition of nutrients to mesocosms at the Marine Ecosystems Research Laboratory (MERL), University of Rhode Island Graduate School of Oceanography (Nixon et al. 1984). Kelly et al. (1985) observed that benthic nitrogen release in the MERL experiment did not increase in a linear fashion with increased nutrient loading. Interestingly, in the MERL systems there was a much tighter relationship between benthic nitrogen release and primary production (Kelly et al. 1985) than there was between nitrogen input and primary production (Nixon and Pilson 1983). This illustrates the tight benthic-pelagic coupling which is frequently observed in coastal systems and points out the important role the sediments can play in controlling water column productivity. Thus, it is important to understand the factors that affect the benthic mineralization of organic matter and nutrient regeneration to fully understand the controls of primary production, and the resulting energy flow, in coastal environments.

An important component of the benthos, the macrofaunal animals, may affect both the magnitude and timing of maximum rates of benthic respiration and nutrient release (Aller 1982, Rudnick & Oviatt 1986). The type and numbers of benthic animals present have important influences on the flux of materials in and out of sediments (Aller 1980, 1982; Rhoads 1974). There is potentially a feedback between benthic animals and water column productivity. Nutrient loading may affect both the number and types of benthic macrofauna present in an environment (Pearson and Rosenberg 1978, Rhoads and Germano 1986), which in turn may affect the release of nutrients from the sediment (Rhoads et al. 1977) and thus affect primary production.

The purpose of this report is to examine the benthic processes, and the factors which influence those processes, that are responsible for the decomposition of organic matter and the recycling of nutrients back to the water column in Buzzards Bay, Massachusetts. This is of particular interest because Buzzards Bay, as is true of most coastal areas, is receiving increased nitrogen inputs as a result of increased anthropogenic activities within its watershed (Buzzards Bay Project Reports). However, Buzzards Bay, in comparison with other nearby areas such as Long Island Sound and Narragansett Bay, receives less nitrogen loading and appears to be relatively unimpacted as yet (Buzzards Bay Project unpublished reports by Turner; Kelly and Valiela; Giblin and Foreman,). This report provides basic data that is necessary to improve our understanding of the role of the benthos in affecting how nitrogen is cycled within Buzzards Bay. A future goal is to use this better understanding of the role of the benthos in regenerating nutrients to construct a quantitative eutrophication model for Buzzards Bay which links nitrogen inputs from land to coastal productivity.

We report here the results of benthic flux measurements, both benthic respiration and benthic dissolved inorganic nitrogen (DIN) release, made over a fifteen month period from June 1988 to September 1989 from one location in Buzzards Bay, MA. We also report the results of flux measurements made from eleven other sites in Buzzards Bay during August 1989. The results of these fluxes are compared to sediment characteristics and benthic macrofaunal abundances determined at the same time.

METHODS

We measured benthic respiration and nitrogen release intensively (11 times) at one site in Buzzards Bay over a fifteen month period from June 1988 to September 1989. Measurements were concentrated in the spring, summer, and fall when flux rates are highest. At the same time, bottom water temperature was recorded and samples were taken to determine sediment characteristic and macrofaunal abundances. The sediment characteristics that were determined were the organic carbon and nitrogen content as well as the chlorophyll \underline{a} and phaeopigment concentration in the surface sediments.

The site chosen for intensive study is near the Weepecket Islands in 15 meters of water (Fig. 1, Weepecket Island Station), this site has been used previously in several biogeochemical studies (Martin and Sayles 1987, Brownawell 1986, McNichol et al. 1988). The bottom at this site consists of the fine silt-clay (Moore 1963) and the benthic animal community is dominated by a <u>Nephtys-Nucula</u> community (as classified by Sanders, 1958). The site is typical of much of the deeper portions of Buzzards Bay (Rhodes & Young 1970; Sanders 1958).

In addition to the Weepecket Island station, we measured benchic respiration and nutrient release at a number of other sites (Fig. 1) during

August 1989 to better characterize flux rates across the bay. We also measured sediment parameters and collected benthic animals at these locations. Several of these sites were along the transect between New Bedford harbor and the central basin of Buzzards Bay that Rhoads and Hampson surveyed with Science Applications International Corporation's sediment profiling camera -REMOTS^(R) (Remote Ecological Monitoring of the Seafloor) (Fig. 1). Station 7, because of its proximity to the New Bedford sewage outfall, was the most anthropogenically loaded site that we sampled. We sampled Station R, which was identified by REMOTS^(R) as a relatively undisturbed benthic regime, as the other, relatively unloaded, end-member of their transect. Because REMOTS^(R) data indicated conditions of increasing organic matter enrichment as one moves shoreward from Station R, we sampled Stations 10, 11, and 14 as representative of intermediate loading levels along the transect. The other sites we surveyed in Buzzards Bay were Stations G, H, K, L, M, and Q (Fig. 1) which were previously sampled by Sanders (1958) for benthic animals. Our choice of sampling locations was skewed towards silty bottom areas which were dominated by a Nephtys-Nucula macrofaunal assemblage and we included only a few stations with sandy sediments (Stations G and H, Sanders 1958). [LORAN coordinates for all stations provided in Appendix I.]

Benthic Respiration and Nutrient Fluxes

At each station 3-4 intact sediment cores were taken by SCUBA diver. These cores were collected in 15 cm inner diameter PVC tubes placed in the sediment by hand. The top of each core tube was sealed while it was still in place in the sediment and the bottom was sealed as soon as the core tube,

containing the sediment, was pulled free of the sediment surface. The tubes contained approximately 30 cm of sediment and 20-30 cm of overlying water. The cores were brought back to the lab and placed in a dark incubator where they were held at <u>in situ</u> temperatures while we measured benthic flux rates. These core tubes were machined to allow them to be sealed with a plexiglass top which was equipped with a magnetic stirrer (Dornblaser et al. 1989). This stirrer gently mixed the water column while we monitored the concentration of oxygen and dissolved inorganic nitrogen species (DIN) in the overlying water throughout the incubation period. Oxygen concentration was measured with a dissolved oxygen meter (Orbisphere 2112 meter) and probe which fit into an opening in the core top. The length of the incubation time, which ranged between 24 and 90 hrs., was determined by the rate of oxygen consumption. Care was taken not to let the oxygen concentration in the overlying water drop lower than 2-4 ppm which would affect benthic animal respiration rates (for effects of low oxygen concentrations on animal respiration rates see Bishop 1952, for example). At least five samples were taken at regular intervals throughout the incubation period. Benthic respiration rate was calculated as the slope of regression of oxygen concentration versus time. Taking at least five time points for each core allowed us to check that the rate of oxygen consumption was linear; any points which deviated significantly from the linear trend were excluded from the regression analysis. In most cases all of the data were included in the analysis.

At the same time the oxygen concentration was measured, samples of the overlying water were withdrawn with syringes through sampling ports to determine the concentration of dissolved inorganic and organic nitrogen. Water samples were held in the syringes for less than an hour until they could be processed. Ammonia concentration was determined for replicate 3 ml samples by the technique of Solorzano (1969) modified for a small sample size. The remaining water in the syringe was frozen for later measurement of the nitrate and nitrite concentration. Nitrate + nitrite were determined together using the cadmium reduction method (EPA) on a rapid flow analyzer (Alpkem RFA-300); the limit of detection was 5 μ M. Previous work suggested that the contribution of nitrite to the dissolve inorganic nitrogen (DIN) pool was insignificant for these sediments so only the combined nitrate + nitrite pool was considered for this study. DIN was calculated as the sum of ammonium + nitrate + nitrite.

Water samples were also taken for the measurement of dissolved organic nitrogen (DON). Recently, it was demonstrated that the technique commonly used to measure DON (persulfate oxidation) greatly underestimates the concentration in seawater (Suzuki et al. 1985). Others in our laboratory are currently working to develop a better technique. When this improved method is available we will determine the DON concentration for our samples; until that time we have preserved the samples by freezing them.

Animals

Three 6.5 cm diameter cores were collected at the same time as the cores for benthic fluxes. The top 10 cm were sieved for macrofaunal animals through a 300 μ sieve and preserved in formalin with rose bengal (see Grassle et al. 1985 for a discussion of sieve sizes). Macrofauna were defined as those animals retained on a 300 μ sieve but excluding those taxa that are traditionally classified as meiofauna (i.e., nematodes, harpacticoid copepods, ostracods). Animals were later counted and identified to at least family level. The major taxa were identified to species.

Sediments

Four smaller cores (2.5 cm diameter) were taken at the same time as the cores for benthic fluxes and animals. Two cores were sectioned into 1 cm intervals to a depth of 10 cm and dried to 105 °C. Carbonates were removed by grinding each section, wetting the sediment and exposing it overnight to concentrated HCl fumes (Hedges and Stern 1984). After acidificaiton, samples were re-dried to 105 °C and analyzed for carbon and nitrogen using a elemental Analyzer (Perkin Elmer 240C CHN).

The top 5-10 cm of the two other small cores were sectioned in 1 cm intervals to analyze for chlorophyll <u>a</u> and phaeopigments. These pigments were extracted from the sediment with cold, buffered 100% acetone (a modification of Foreman 1989). The sediment acetone mixture was centrifuged and the absorbance of the supernatant at 665 and 750 nm was measured on acidified and unacidified samples. The equations of Lorenzen (1967) were used to calculate chlorophyll <u>a</u> and phaeopigments.

RESULTS AND DISCUSSION

Benthic Fluxes

Benthic respiration and benthic DIN release rates at the Weepecket Island Station followed annual variations in temperature fairly closely during 1988 and 1989 (Fig. 2). The maximum rates of benthic respiration and DIN release (23.8 mmol $O_2 m^{-2} d^{-1}$ and 4.1 mmol N m⁻² d⁻¹, respectively) were observed in August when the water temperature was highest. The lowest rates were observed during the winter and early spring when the water temperature was below 10°C. The lowest benthic respiration (6.4 mmol $O_2 m^{-2} d^{-1}$) was observed in January when the water temperature was 6.6 °C. The lowest DIN release rate (0 mmol N m⁻² d⁻¹) was observed in March when the water temperature was 3.4 °C.

An exception to this close correspondence between flux rates and temperature was seen during the late spring. During March, April and May, benthic respiration increased rapidly relative to temperature changes. In fact, benthic respiration began increasing while the temperature was still dropping in March. The second highest oxygen uptake rate of the year at the Weepecket Island Station (22.6 mmol $m^{-2} d^{-1}$) was observed in early May and was nearly as large as the maximum rate (23.8 mmol $m^{-2} d^{-1}$) observed later in August.

The pattern of DIN release at the Weepecket Island Station during the spring was different than that for benthic respiration. A spring maxima was not observed until June. During March, April and May, when benthic respiration rates increased dramatically, DIN release rates were low and appeared to lag behind the temperature changes.

Integrating the area under the benthic respiration and benthic nitrogen flux curves in Figure 2 provides an estimate of the annual consumption of oxygen of 5,210 mmol $O_2 m^{-2} yr^{-1}$ and an annual release of nitrogen of 686 mmol N m⁻² yr⁻¹ for the Weepecket Island site. Assuming a carbon to oxygen equivalence ratio of 1:1 for aerobic decomposition (Fenchel and Blackburn 1979), this corresponds to an oxidization of 63 g C m⁻² yr⁻¹ (Table 1). When we add the amount of carbon that is oxidized via sulfate reduction and permanently stored as reduced sulfur (Banta et al., unpub. data), and therefore is not reflected in the 0_2 consumption, our estimate increases to 65-80 g C m⁻² yr⁻¹.

Benthic respiration rates measured from several locations in Buzzards Bay during August 1989 ranged from a low of 18.8 mmol $O_2 m^{-2} d^{-1}$ at Station R to a high of 27.9 mmol $O_2 m^{-2} d^{-1}$ at Station M (Fig. 3a). Water temperature was essentially constant (20.6-22.6 °C) over the three week period in which we made our measurements. The sediment DIN release rates follow roughly the same pattern among the stations as benthic respiration although there was a greater difference between sites (Fig. 3b). The lowest DIN release rate (2.0 mmol N $m^{-2} d^{-1}$) was observed at Station K and the highest rate (5.0 mmol N $m^{-2} d^{-1}$) was observed at Station M (Fig. 3b).

Both the benthic respiration and the DIN release rates measured along the transect away from the New Bedford sewage outfall (Stations 7-R, Fig. 1) show the effect of the nutrient inputs and organic matter loading from the outfall. The highest rates were observed at Station 7 with a steady decrease when moving from Stations 10, 11, and 14 to the lowest rates at Station R (Fig. 3). Note however, that other locations in Buzzards Bay (e.g., Station M) show benthic respiration and DIN release rates as high as Station 7. The location of Station 7 is probably far enough away from the outfall (3.1 km) that these flux rates do not reflect the intense "near-field" effects of the sewage sludge deposition and extremely high nutrient concentrations; one would expect much higher benthic respiration and DIN flux rates directly adjacent to the outfall.

Our observed benthic respiration rates are comparable, but tend to be somewhat lower than those measured by others in Buzzards Bay (Table 2a). Smith et al. (1973) and Rowe et al. (1975), working at Sanders' (1958) Station J (located between Station K and Woods Hole (see Fig. 1)), and B. Howes (pers. comm.), who measured benthic respiration rates of 12-38 mmol O_2 m⁻² for stations located in outer New Bedford Harbor between September 1988 and July 1989, found benthic respiration rates that were generally faster than ours for a comparable temperature. The sediments Howes studied were undoubtedly more influenced by organic loading from the New Bedford sewage outfall than the stations we examined, so higher respiration rates in outer New Bedford Harbor, relative to the open regions of Buzzards Bay, are not surprising. In addition, some of the differences between our results and those of others are likely due to the spatial variability in benthic fluxes present in Buzzards Bay (see Fig. 3).

It is interesting to note that our annual carbon oxidation budget of 65-80 g C m⁻² yr⁻¹, based on benthic respiration rates, agrees quite well with McNichol et al. (1988) who estimated that 69 g C m⁻² were oxidized annually at the Weepecket Island site. They based their estimate on changes in dissolved inorganic carbon porewater profiles over a seasonal cycle. However, both of these estimates are significantly lower than the 142 g C m⁻² yr⁻¹ estimate of Rowe (pers. comm.) based on flux measurements near Station J (Rowe et al. 1975). At this time it is not possible to give a satisfactory explanation as to why there is spatial discrepancy in the benthic respiration rates and annual carbon oxidation estimates reported for Buzzards Bay.

When all of the benthic respiration rates for Buzzards Bay (Fig. 2a, Table 2a) are compared to respiration rates for other coastal environments (Table 2b) we see that in general, the rates for Buzzards Bay are somewhat lower. This implies that the sediments in Buzzards Bay are oxidizing less organic matter than many other coastal areas. Lower benthic respiration is consistent with lower concentrations of chlorophyll <u>a</u> (Rhodes et al. 1975, Roman and Tenore 1978) and lower primary production (Roman and Tenore 1978) in Buzzards Bay than in many other coastal areas (see data in Nixon and Pilson 1983). More recent estimates of chlorophyll <u>a</u> concentration (Turner 1989) and primary production (Smayda 1989) for Buzzards Bay are somewhat higher than those previously reported by Rhodes et al. (1975) and Roman and Tenore (1978), but even with these higher estimates Buzzards Bay appears to be less productive than many other coastal areas.

In contrast to benthic respiration, our observed DIN flux rates (Fig. 2b, 3b) agree more closely with those reported by others both for Buzzards Bay and elsewhere (Table 2). Our observed DIN release rates, which ranged from a low of 0 mmol $m^{-2} d^{-1}$ in March 1989 at the Weepecket Island site to a high of 5.0 mmol $m^{-2} d^{-1}$ in August 1989 at Station M, completely overlap with the range reported by others for Buzzards Bay (Table 2a). Both higher and lower DIN flux rates are reported for other coastal areas (Table 2b), but the rates from Buzzards Bay (Fig. 2b and 3b, Table 2a) correspond well to the lower half of the range of DIN flux rates reported by others (Table 2b). It is worth noting, however, that DIN flux rates tend to be more variable than benthic respiration rates, so it is not surprising that the range of observations would overlap. That caveat aside, the very close agreement between all of the studies for DIN release rates, in contrast to the differences in benthic respiration rates, is striking.

The ratio of moles of oxygen consumed to moles of nitrogen released by the sediments at the Weepecket Island site on an annual basis for 1988-89 was 15.2 (Table 1). This value is slightly higher than 13.25, which is the expected value for the aerobic decomposition of phyto-detritus containing carbon and nitrogen in the Redfield (1934) ratio of 106:16 (Nixon et al. 1976). This suggests that less nitrogen is being released from the sediments than is expected from the amount of organic matter being mineralized. One common explanation for this discrepancy is that the "missing" nitrogen is lost through denitrification (Nixon et al. 1976, 1981). If we make the assumption that organic matter with a Redfield (1934) C/N ratio is being aerobically decomposed in the sediments of Buzzards Bay, we calculate that denitrification may be removing up to 12.8% of the nitrogen being mineralized in the sediments on an annual basis (Table 1). This value is lower than the estimates of denitrification from many other coastal marine environments, made either by direct measurements of denitrification (Seitzinger et al. 1984) or as implied from O/N ratios (Nixon 1981, Table 2). Denitrification is thought to account for the loss of as much as 70% of the nitrogen deposited in coastal sediments in some cases, but more typical values range from 15% to 60% (Seitzinger 1988). Our calculation suggests that Buzzards Bay has fairly low rates of denitrification and is fairly efficient at recycling nitrogen back to the overlying water.

We observed a great deal of variability in the O/N flux ratios at the Weepecket Island site over the course of the year. The very large O/N ratios seen in the spring suggest that denitrification was most important at that time (Fig. 4). These high O/N ratios coincide with the time of the year when the sediments in Buzzards Bay receive a large input of fresh detritus following the winter/spring phytoplankton bloom (Roman and Tenore 1978). A spring maxima in denitrification rate related to the deposition of phytodetritus following phytoplankton blooms (Jensen et al. 1988) or following peaks in benthic primary production (Jorgensen and Sorensen 1985) have been reported for other coastal areas.

The O/N flux ratios observed across the Bay in August 1989 ranged from a low of 11.2 at Station M to a high of 22.6 (Fig. 5). Several stations (7, G, H, M and the Weepecket Island) showed values quite close to the expected value of 13.25 suggesting quite efficient recycling of nitrogen back to the overlying water at that time. The other stations had values ranging from 15.5 to 22.6 which are more typical of those measured in other coastal areas (Table 2). It appears that stations closer to the outfall along the New Bedford transect are recycling nitrogen more efficiently than those further away. When comparing all of these stations it is important to keep in mind that these measurements were made in August when we observed some of the lowest O/N ratios at the Weepecket Island Station (Fig. 4). Given the variability over time observed at the Weepecket Island site it is important to be careful when interpreting O/N flux ratios measured only once. However, it appears that Buzzards Bay is fairly efficient at recycling nitrogen from the sediments at least at that time of the year. One might expect the differences in recycling efficiency between stations, and presumably denitrification, to be even greater in the spring.

It is worth mentioning that processes other than denitrification may lead to O/N ratios other than 13.25. If much of the organic matter is being

mineralized anaerobically and the reduced by-products (e.g., sulfides) are permanently stored (not reoxidized) then the resulting consumption of 0, will be less for a given amount of organic matter mineralized. This would lead to a lower O/N ratio. However, as we previously estimated, only a small portion (2-21%) of the reduced sulfur compounds produced from sulfate reduction are permanently buried on an annual basis in Buzzards Bay (Banta et al. unpub. data). There are other processes, on the other hand, that could lead to higher O/N ratios. An alternate explanation for the large O/N discrepancy in the spring is that the animals and microbes living in the sediment are quite nitrogen limited in the spring and as a result any of the nitrogen mineralized from organic matter is sequestered and not released back to the overlying water (Marsh and Tenore 1990; D. Rice, pers comm.). The possibility of nitrogen limitation was increased in the spring because of the presence of benthic diatoms which we occasionally observed during that time of the year. Another mechanism that leads to higher O/N ratios is when a substantial proportion of the benthic nitrogen release is in the form of DON, which we did not measure. It is generally thought that the release of DON from sediments makes up only a small portion of benthic nitrogen fluxes (Nixon 1981) although DON release can be significant in some environments (Blackburn 1987). Finally, the expected O/N ratio from benthic fluxes would be different than 13.25 if the organic matter that was being mineralized in the sediments had a C/N ratio significantly different from that given in Redfield (1934).

It is worth keeping these other processes in mind when trying to interpret O/N flux ratios in terms of potential denitrification. It is also likely that these other processes have seasonal differences in their effects on altering O/N flux ratios. For example, it is possible that the high O/N ratios in the spring at the Weepecket Island Station were due to both denitrification and nitrogen limitation. Whatever the mechanisms involved, it is apparent that the seasonal dynamics of temperature and organic matter inputs are likely to be quite important in affecting the efficiency of the recycling of nitrogen in Buzzards Bay sediments.

Sedimentary Carbon and Nitrogen Content

Profiles of the organic carbon and nitrogen content of the sediment at the Weepecket Island Site showed little variation over an annual cycle. In representative profiles from four different times during 1989, the carbon content was 2.2-2.5% for the surface sediments and decreased gradually with depth to values of slightly less that 2% at depth (Fig. 6). A similar pattern was observed for nitrogen which decreased from 0.3-0.4% at the surface to 0.2-0.3% at depth. There was little seasonal change in the shapes or magnitudes of these profiles (Fig. 6).

A second way to examine the carbon and nitrogen content is to calculate an integrated carbon and nitrogen concentration for the sediment. Because most of the changes in sedimentary profiles occur in the upper portions of the sediment (Fig. 6) we summed the carbon and nitrogen concentration for the top 5 cm to calculate an integrated sedimentary carbon and nitrogen concentration. There was little seasonal change in either integrated carbon or nitrogen concentrations at the Weepecket Island Station (Fig. 7). There was a slight increase during the summer of 1989 of the sediment stores of carbon. In contrast, nitrogen stores decreased slightly from a spring maximum in early May. In the same representative profiles there was little variation in the C/N ratio over the course of the year or with depth within the sediment; the C/N ratio was usually 7-8 (Fig. 8). The only exception to this was in July when the surface sediments had a C/N of 10.8. Note that there was a tendency for the C/N ratio to be slightly lower in May throughout the entire sediment than at other times of the year (Fig. 8).

The highest carbon and nitrogen contents among the stations we surveyed in August 1989 were measured at Station H which had concentration of 2.6% C and 0.35% N in the surface sediments (Fig. 9). The lowest carbon and nitrogen contents were measured at Station G which had concentrations less than 0.4% C and less than 0.05% N. The C/N ratio of the sediments from these stations ranged between 7 and 10 for the most part (Fig. 10). The highest C/N ratios were observed from Station G with a maximum of 10.4 at 1-2 cm (Fig. 10). The lowest C/N ratios were observed at Stations K and R, with many values quite close to 7 (Fig. 10). As was the case with the Weepecket Island site throughout the year, there was little change in C/N ratio with depth at any of the stations (Fig. 10).

Our sediment organic carbon contents agree well with other determinations made in Buzzards Bay. Sanders (1960) and Whitlach (unpub. data) have organic matter loss on ignition data (LOI) for Station R. Their LOI values are 6-7% which, using a conversion factor of 0.4 (which assumes the organic matter has approximately the same %C as carbohydrates), corresponds to 2.4-2.8% C. McNichol et al. (1986) reported carbon concentrations of 2.0-3.4% for surface sediments and 1.5-1.6% for deeper sediments at the Weepecket Island site.

The sediment carbon content in Buzzards Bay is similar to other coastal embayments with silty bottoms. Aller and Yingst (1980) reported summer sediment carbon concentrations of approximately 2.0-2.5% for surface sediments and 1.6-2.2% for deeper sediments from two stations located in central Long Island Sound. In general, the organic-rich muds of Long Island Sound have a range of 2-4% organic carbon (Mackin and Swider 1989).

The surface organic carbon concentrations of Narragansett Bay sediments typically range between 0.5-4% (Oviatt and Nixon 1975, Nixon et al. 1980). This was also true in the MERL eutrophication experiment (June 1981-September 1983, see Nixon et al. 1984) except when extreme nutrient loadings resulted in higher primary production than is typical for Narragansett Bay. In those cases in the MERL experiment the carbon content of the surface sediments increased from a starting concentration of approximately 2% to as high as 5% following the deposition of the winter/spring phytoplankton blooms to the sediments (Sampou and Oviatt 1990).

The C/N ratios we measured for Buzzards Bay, which range typically between 6 and 8, are towards the lower end of the range of C/N ratios reported for marine sediments. A typical C/N value for coastal marine sediments is 10-12 (Degens 1970, Blackburn 1987). However, others have measured lower C/N ratios for coastal marine sediments (Giblin, unpub. data; McNichol, unpub. data; Blackburn 1987; Grebmeyer et al. 1988). Our values for Buzzards Bay are close to the C/N values for phytoplankton (6-7) (Fenchel and Blackburn 1979). This might suggest that Buzzards Bay receives fairly frequent inputs of planktonic organic matter, or that the planktonic organic matter it receives is decomposed rather slowly and its C/N signal persists in the sediments for some time. Sampou and Oviatt (1990) observed the C/N ratio of the surface sediments in the MERL mesocosms dropped to 7-8 during the early summer following the deposition of phyto-detritus from the spring blooms. This is in contrast to sediment C/N ratios of 10-12 which they observed during the rest of the year (Sampou and Oviatt 1990).

Sedimentary Pigments

Four representative profiles of sedimentary pigment concentrations are shown in Figure 11. During most of the year, and at most depths within the sediment, the concentration of phaeopigments, which are degradation products of chlorophyll, is considerably higher than chlorophyll <u>a</u>. Phaeopigments were slightly elevated in the surface sediments but concentrations remained fairly high (15-20 μ g/cc) even at deepest portions of all the sediment profiles we examined. In contrast, chlorophyll <u>a</u> concentrations were quite low (with the exception of the surface sediments during May 1989) and dropped quickly to below 5 μ g/cc for depths greater than 2 cm. Note, however, that chlorophyll was detected at all depths within the sediment at all times of the year. This background amount of chlorophyll <u>a</u> probably represents some complexed or refractory form of chlorophyll that persists in the sediment. This refractory chlorophyll is probably not a good indicator of recent inputs of planktonic material.

In contrast to carbon and nitrogen, the sedimentary store of pigments (again summed for the top 5 cm) showed significant seasonal variation (Fig. 12). The sediment chlorophyll <u>a</u> pool was quite low throughout the year except during the spring when there was a sharp increase in chlorophyll <u>a</u> content. This elevated concentration quickly disappeared in the next few months. The seasonal pattern for phaeopigments is more erratic but there is a suggestion of a fall peak, as well as possibly a spring peak in the phaeopigment pools in the sediments. The integrated total pigment concentration follows the seasonal pattern for phaeopigments for the most part (Fig. 12). This is not surprising given that the sedimentary pool of pigments is dominated by phaeopigments for most of the year. However, the total pigment pools show the existence of the late spring and late summer/early fall maxima more clearly than either the integrated chlorophyll <u>a</u> or phaeopigment concentrations alone.

The sediment profiles of phytoplankton pigments for other stations in Buzzards Bay that we sampled in August 1989 all show fairly similar patterns between stations (Fig. 13). All have low concentrations of chlorophyll <u>a</u> with 3-10 times higher concentrations of phaeopigments. All of the stations show higher concentrations of phaeopigments in the surface sediments than at depth within the sediment. However, only Stations K, H, L, and 14 have chlorophyll <u>a</u> concentrations at the surface that are higher than at depth. The sedimentary stores of pigments for these stations ranged between 95 mg m⁻² (Station 7) and 188 mg m⁻² (Station L) for chlorophyll <u>a</u> and between 466 mg m⁻² (Station G) and 1021 mg m⁻² (Station Q) for total pigments (Fig. 14).

Roman and Tenore (1978) found lower sedimentary pigment concentrations at a site near Station K than we did for Buzzards Bay in general. They reported sedimentary chlorophyll <u>a</u> concentrations integrated for the top 5 cm ranging from approximately 20 to 80 mg m⁻² during 1975. They found the period of maximum sediment chlorophyll <u>a</u> content to be February through May and attribute this chlorophyll <u>a</u> to both pelagic and benthic phytoplankton. We observed our peak of sedimentary chlorophyll <u>a</u> during May and early June for 1989, but we did not sample during April. However, our background level of chlorophyll <u>a</u> at the Weepecket Station of approximately 170 mg m⁻² is higher than any of the integrated chlorophyll <u>a</u> concentrations measured by Roman and Tenore (1978). Some of stations we studied with lower integrated chlorophyll <u>a</u> concentrations (Fig. 14) such as Stations 7, 10, G, M and R are closer to the maximum integrated concentrations reported by Roman and Tenore (1978).

Our sedimentary depth profiles agree qualitatively quite well with those reported by Sun et al. (1990) for two locations in Long Island Sound. They found chlorophyll <u>a</u> was distributed within the sediment with a surface or subsurface maximum. Below this maximum the chlorophyll <u>a</u> concentration decreased in an exponential manner. We saw similar profiles in Buzzards Bay (Figs. 11 and 13), especially in the spring, however Buzzards Bay sediments tended to have more chlorophyll <u>a</u> present at depth and as a result Buzzards Bay had higher total amounts of chlorophyll <u>a</u> in the sediment than Long Island Sound by roughly 2-10 fold for comparable times of the year.

Based on these other studies it appears that we found fairly high concentrations of chlorophyll <u>a</u> in the sediments of Buzzards Bay, especially at depth. One possible conclusion from these results is that others have underestimated or that we have overestimated the chlorophyll <u>a</u> concentration in sediments with the different methods used in these studies. The chlorophyll extraction technique of Tietjen (1968) used by Roman and Tenore (1978) uses shorter extraction times than the technique we used. This is one possible reason that we observed higher concentrations of chlorophyll in the sediments of Buzzards Bay than they did. It is unlikely that we have overestimated chlorophyll <u>a</u> relative to Sun et al. (1990) because they used multiple extractions with 100% acetone while we only used a single, but longer, extraction. They also found a bound chlorophyll <u>a</u> pool that was only extractable after freezing the sediments. We extracted all of our sediments shortly after they were collected and we did not freeze our sediments. This would suggest that, if anything, we should have underestimated sediment chlorophyll <u>a</u> concentrations relative to Sun et al. (1990). The higher chlorophyll <u>a</u> concentrations we saw at depth in the sediment would suggest that benthic animals, or some other mixing mechanism, is responsible for distributing chlorophyll <u>a</u> to depth once it is deposited or produced on the sediment surface (Sun et al. 1990).

Benthic Macrofauna

Total macrofaunal abundances at the Weepecket Island site ranged between 25,000 and 60,000 individuals m⁻² during 1989-90 (Fig. 15). There was a tendency for animal numbers to be lower in the summer, however, at this sampling frequency and considering only total abundances it is difficult to attribute this seasonal pattern to any specific recruitment (e.g., larval settlements) or mortality events (e.g., predation). Total macrofaunal abundances of the twelve sites we sampled in Buzzards Bay during August 1989 ranged from a low of 21,000 m⁻² at Station G to a high of 106,000 m⁻² at Station M (Fig. 16).

The macrofaunal community over the season at the Weepecket Island site and for most of the other stations we examined in Buzzards Bay were fairly similar. <u>Nucula annulata</u>, a small bivalve, was the most abundant organism at most of the stations in Buzzards Bay (Fig. 17a, 18). <u>Nucula</u> usually made up between 30 and 80% (by numbers) of the macrofaunal community. The major exception was Station G which had relatively few <u>Nucula</u> present (15% of the total animals). <u>Nucula</u> showed less variation in abundance throughout the year at the Weepecket Island Station than most of the other species, although its numbers were slightly lower in the fall than during the rest of the year (Fig. 17a).

<u>Cylichna oryza</u>, a small gastropod, was another fairly common mollusc in the benthic community of Buzzards Bay (Fig. 17a, 18). Its numbers were lower and more variable (it ranged between 0 and 19%), both between stations and over time at the Weepecket Island Station, than for <u>Nucula</u>. <u>Cylichna</u> showed maximum abundances in spring and fall at the Weepecket Island Station.

In contrast to the molluses, the abundances of polychaetes were quite variable (Fig. 17b, 18). <u>Mediomastus ambiseta</u>, a small Capitellid polychaete, was an important member of the Buzzards Bay macrofaunal community although it had the greatest variability in numbers of any species, both over time and space across Buzzards Bay. <u>Mediomastus</u> made up anywhere between 3 and 56% of the benthic community. The was also a great deal of variability on small spatial scales in the numbers of <u>Mediomastus</u> which can be seen from the very large standard errors for each sampling date derived from three replicate samples taken within approximately a meter of each other (Fig. 17b, 18). From the seasonal data at the Weepecket Island Station it appears that there is a fall recruitment event when the abundance of <u>Mediomastus</u> increases dramatically. So, while at times <u>Mediomastus</u> is the dominant member of the macrofaunal community, its importance is quite variable both from place to place and time to time.

Patterns of abundance similar to those for <u>Mediomastus</u>, including increased fall and winter abundances, were observed for the Spionid polychaetes, although the absolute densities of Spionids were lower than those of <u>Mediomastus</u> (Fig. 17b, 18). Spionids usually made up only a few percent of the animal numbers although occasionally they represented 10-15% of the total animal populations.

The third common polychaete of the benthic community in Buzzards Bay, <u>Nephtys incisa</u>, showed low and relatively constant abundances in all of the samples examined relative to many of the other major macrofauna taxa. However, it is important to point out that <u>Nephtys</u> are the largest individuals of the common taxa of the macrofaunal community and as such, numbers alone underestimate its importance to benthic processes. <u>Nephtys</u> showed a different pattern of abundance than the other two common polychaetes, <u>Mediomastus</u> or the Spionids, and had lower numbers in the winter than during the rest of the year (Fig. 17b).

The five common "species" just discussed usually make up 75 to 91% of the macrofaunal community in Buzzards Bay with other macrofaunal species making up the remaining 9-25% (Fig. 17c, 18). The exception to this was Station G, where the "other" species represented 40% of animals present. Station G had the sandiest sediments of the locations that we sampled and many of the species we found there were more typical of the sandier regions of Buzzards Bay (Sanders 1958).

Our total macrofaunal abundances are 3 to 96 times higher than those of Sanders (1958) who observed a range of 1100 to 6100 individuals m^{-2} from nine muddy stations in Buzzards Bay during October and November 1955. Our macrofaunal densities do agree more closely with R. Whitlach (unpub. data) who revisited Sanders' (1958) Station R in 1975-76 and found on an annual average of 62,000 individuals m⁻². Whitlach also made a direct test comparing the sampling and sorting methodologies of Sanders (1958, 1960) versus more recent techniques (such as those used by Whitlach and us) and concluded that Sanders' techniques may underestimate abundances by approximately 50%. The problem of underestimation is especially pronounced for small animals, such as <u>Mediomastus</u>, which may be underestimated by as much as 500% (Whitlach, unpub. data). Correcting for differences in abundances between the studies due to biases from sorting techniques may not be enough to explain the 3 to 96-fold difference that we observed. However, we concur with Whitlach that it is not possible to distinguish whether these are due to differences in sorting techniques or to an increase in macrofaunal abundances since the 1950's. The similarity between our data and that of Whitlach does indicate that there has not been a change in macrofaunal abundances in Buzzards Bay since the 1970's.

Despite these differences in abundances between the results of Sanders (1958, 1960) and the more recent data of Whitlach and ours, it appears that the macrofaunal community structure in the muddy sediments of Buzzards Bay were very similar in all these studies. If we ignore spatial and seasonal variability and combine all of the abundance data into a composite list we see that all three studies show the same common species (Table 3). There is very good agreement of the macrofaunal community structure between our study and that of Whitlach. Sander's results also yield roughly the same species assemblages except for the absence of the small polychaetes, <u>Mediomastus</u> and Paraonids, which were likely to be underestimated given the differences in techniques between the studies as discussed earlier. Based on the comparison of these studies of the benthic macrofauna in Buzzards Bay, it appears that the structure of the benthic community in the muddy sediments of Buzzards Bay is fairly constant, both between locations and over time. Obviously, the macrofaunal community is different in the sandier areas of Buzzards Bay (our data, Station G; Sanders 1958).

The macrofaunal community of Buzzards Bay is similar to muddy bottom communities in Long Island Sound and Narragansett Bay. The community in Long Island Sound has been characterized as a <u>Nephtys-Yoldia</u> (a Nuculanid bivalve) assemblage although <u>Nucula</u> was also quite common throughout the Sound (Sanders 1956). Sanders (1956) reported macrofaunal abundances ranging between 5500 m⁻² and 46,000 m⁻² for several stations in Long Island Sound. These abundances are lower than we found for Buzzards Bay. The differences, however, may be attributed in part to the different sorting methodologies used in the two studies as previously discussed.

The lower and middle regions of Narragansett Bay are numerically dominated by <u>Mediomastus</u>, <u>Nucula</u> and <u>Yoldia</u> (Grassle et al. 1985). Other larger, but less numerous animals, which are important in the community are <u>Nephtys</u>, <u>Asychis elongata</u> (a Maldanid polychaete) and <u>Pitar morrhuana</u> (a Venerid bivalve) (Grassle et al. 1985). Grassle et al. (1985) used nearly identical macrofaunal sampling and enumeration techniques so their reported abundances, ranging between 20,000 and 160,000 m⁻², are directly comparable, and somewhat greater than our densities for Buzzards Bay.

The benthic communities of both Long Island Sound and Narragansett Bay have undergone long-term shifts in macrofaunal species assemblages since the 1950's, presumably due in part to eutrophication and other anthropogenic disturbances (Reid 1979, Grassle et al. 1985). In contrast, making as reasonable a comparison as possible with the benthic communities of Buzzards Bay in the 1950's, and taking into account biases due to different methodologies (Whitlach, unpub. data), there is no convincing evidence that the benthic community of Buzzards Bay has changed significantly in the last thirty years. One possible exception is that <u>Yoldia</u> appears to be less abundant than it was previously (Rhoads, pers. comm.).

Controls of Benthic Fluxes

We used multiple regression and path analyses (Sokol and Rolf 1981) to assess which of the environmental and sediment parameters we measured could predict the benthic flux rates we observed at the Weepecket Island Station (Table 4). The variables that were tested in the analysis were temperature, sediment carbon content, sediment nitrogen content, sediment chlorophyll <u>a</u> concentration, sediment phaeopigment concentration and total macrofauna abundance. For these analyses a Q_{10} relationship between the fluxes and temperature was estimated from the data and it was this exponential Q_{10} relationship that was used in the regression and path analyses to assess the predictive power of temperature. The Q10 values calculated from our Weepecket Island Station data for benthic respiration and DIN flux were 1.89 and 1.63 respectively. (The regression and path analyses were repeated with an assumed Q_{10} value of 2.0 for both oxygen and DIN flux and the results were not appreciably different.) The advantage of doing a path analysis combined with the regression analyses over doing a multiple regression analysis alone is that we were able to assess which apparent causal relationships between the independent variables (sediment parameters) and the dependent variables

(benthic fluxes) were simply due to correlations with other independent variables which also affect the fluxes (see Sokol and Rolf?).

Based on these analyses, we can explain 77% of the pattern we observed in the benthic respiration rates at the Weepecket Island Station over the seasonal cycle by knowing the bottom water temperature and the concentration of chlorophyll <u>a</u> (Table 4). For benthic respiration, the multiple regression analysis indicates that adding any other independent variables to this relationship does not significantly improve our ability to predict the observed fluxes. Neither temperature nor sediment chlorophyll <u>a</u> concentration when regressed against benthic respiration alone explain much of the variation in benthic respiration and, in fact, the sum of the amount of variability they each explain in univariate regressions versus benthic respiration is much less than the variability that they explain when combined in a multiple regression. In both cases there is a positive relationship between the variables and benthic respiration; that is, as temperature or chlorophyll a increases so does benthic respiration. The positive relationship with temperature is not surprising given that the metabolism of the benthic community, from the bacteria through the macrofauna, is controlled by temperature to a great extent. It is encouraging that the estimated relationship between benthic respiration and temperature is quite close to a Q_{10} of 2.0; Q_{10} values ranging between 2 and 3 are common for biological reactions (Valiela 1984). However, others have found benthic respiration rates conforming to Q_{10} 's closer to 3 (Rudnick and Oviatt 1986). The positive relationship between benthic respiration and sediment chlorophyll a concentration suggests that the benthos is fueled by, and dependent on, inputs of organic matter from the overlying

water and possibly from benthic primary production.

Some of the chlorophyll <u>a</u> we measured in the sediments may have originated from benthic diatoms. Although light penetration in Buzzards Bay is often significant enough for sufficient light to reach the bottom to support benthic primary production (Turner 1989), we have only infrequently observed the presence of benthic diatoms at the sites we have sampled. It may be that some mechanism other than light penetration keeps diatom abundances low. However, a noticeable diatom mat was present at the Weepecket Island site in May 1989 when we measured the high concentrations of sediment chlorophyll a. It is likely that much of this increased chlorophyll in the spring represented the deposition of phyto-detritus from the spring phytoplankton bloom to the benthos given the timing of these blooms in Buzzards Bay (Turner 1989). More recently, in the spring of 1990, we measured rates of net photosynthesis for some benthic diatoms that we found at the Weepecket Island site and the rates appeared to be fairly low. However, the potential role of benthic diatoms, both as producers and consumers of organic matter, on the benthic fluxes of Buzzards Bay needs to be examined further. Whether the chlorophyll was of planktonic or benthic origin, there was a higher chlorophyll <u>a</u> concentration in the surface sediments in the spring and at the same time we measured a dramatic increase in benthic respiration.

The results of the regression and path analyses for DIN flux rates are similar to those for benthic respiration in that temperature and, in this case, phaeopigment concentration, explain most (92%) of the variation in DIN release rates from the sediments at the Weepecket Island site over the year (Table 4). However, there are some important differences in the results for

DIN fluxes versus benthic respiration. For DIN flux, most of the pattern (85%) can be explained by temperature alone. The multiple regression analyses suggest that we can improve on our ability to predict DIN release rates to nearly 100% by also knowing the sedimentary carbon and nitrogen content, the phaeopigment concentration and the macrofaunal abundances. However, the path analysis suggests that most of the apparent causative relationships between DIN flux rate and most of these other variables is due to correlations between many of the independent variables. The path analysis suggests that, aside from temperature, the only variable that provides any additional independent (uncorrelated) information about DIN flux rates is the sediment phaeopigment concentration. This leads to the simpler statistical model presented in Table 4. In this case DIN release rate is positively related to temperature, as was benthic respiration, but negatively related to phaeopigments in the sediment. The reason for this negative relationship is not clear because at this point we do not understand what is controlling the amount of phaeopigments in the sediments over the course of the year. If the conversion of chlorophyll a to phaeopigments indicates the aging of recently deposited phyto-detritus in the sediments then this inverse relationship might suggest that the release of nitrogen from the sediment decreases as recently deposited organic matter ages and persists in the sediment, becoming lower in quantity and poorer in quality.

Regression and path analyses were also performed to attempt to explain the pattern of benthic fluxes observed between the twelve stations we sampled in Buzzards Bay during August 1989. Because these stations had approximately the same bottom water temperatures when they were sampled we did not include temperature as an explanatory variable in these analyses. However, none of the other independent parameters (sedimentary carbon and nitrogen, chlorophyll a and phaeopigment concentration or benthic macrofauna) were correlated with either benthic respiration or DIN release rates and as a result none of these parameters were useful for predicting benthic fluxes (Table 5). It is important to keep in mind that these data represent the relationships between these parameters at one time of the year, and as such, it is not completely surprising that they were less informative than data representing the relationships between the same parameters over a seasonal cycle in one location (i.e., for the Weepecket Island Station). This is especially true if many of the benthic processes in Buzzards Bay are controlled by events occurring in the spring as the Weepecket Island data would suggest. It is also likely that other factors which we did not measure or could not quantify are important for explaining why benthic fluxes are high at Stations 7 and M and low at Stations K and R, for example. Factors which affect the rate of delivery of organic matter to the sediments, such as water circulation, sedimentation rates, and localized primary production are undoubtedly quite important.

We learn something as well about the factors controlling benthic fluxes in Buzzards Bay by examining those variables which were not useful for predicting benthic fluxes for any of the cases examined. In no case did knowledge of the sediment carbon or nitrogen content or the abundance of benthic macrofauna help explain benthic respiration or DIN flux. It was especially surprising that sedimentary carbon and nitrogen was not useful for explaining any of the differences between fluxes that we measured for the twelve stations in Buzzards Bay, given the large range of carbon and nitrogen concentrations observed (Fig. 9). This might suggest that the sedimentary stores of carbon or nitrogen at any site represent the remnants of organic matter that has been deposited and mineralized (Marshall 1972), while benthic fluxes reflect the current mineralization of a small amount of more reactive organic matter that is not measurable in the bulk sediment organic matter pool. Our data suggests that sedimentary pigment content is likely to be a better indicator of this more reactive organic matter than percent carbon or nitrogen.

In Buzzards Bay we could not detect any effect of the macrofauna on benthic metabolism. It appears that the direct contribution of benthic macrofauna to benthic metabolism in Buzzards Bay is small; however, the presence of animals is important for maintaining microbial processes at higher rates at certain times of the year in this environment (Banta, in prep.). The small direct contribution to benthic fluxes due to animal respiration and excretion in Buzzards Bay is in contrast to some other coastal areas where the benthic macrofaunal community has been estimated to contribute 20-50% to benthic respiration and DIN flux (Banse et al. 1971, Smith et al. 1973, Kelly 1983).

Although we did not quantify sediment grain size, it appears that the benthic flux rates we observed in Buzzards Bay were independent of bottom type. The two sandiest stations we sampled (Stations G and H, Sanders 1958) had benthic respiration and DIN release rates that fell in the middle of the rates observed for all the rest of the stations which were characterized by muddy bottoms (Fig. 3). It is likely that the most important factor
controlling the rates of benthic processes is the loading of materials to the sediments and not the physical structure of the sediment environment. This premise is supported by the reduction of flux rates as you move away from the organic matter loading of the New Bedford sewage outfall (Fig. 3) as well as the importance of organic matter supply to the sediments. If a more extensive survey of bottom types was made, one might expect a relationship between fluxes and sediment texture to the extent that the grain size distribution reflects areas of sediment (and organic matter) focusing or dissipation. In our limited survey of differing bottom types (most of our stations were silty mud) we did not find such a relationship.

MANAGEMENT IMPLICATIONS

An important goal of this study was to add to the basic understanding of the benthic processes responsible for the cycling of nitrogen within Buzzards Bay in the hope that this information will be useful when designing and implementing management strategies to help control the eutrophication of Buzzards Bay. In this section we summarize the observations and conclusions from this study that may have implications for management issues.

To help address whether there have been long term changes in the community structure and the productivity of Buzzards Bay, it is useful to compare Buzzards Bay to other nearby coastal environments. Our results would suggest that benthic flux rates, especially benthic respiration, in Buzzards Bay are lower than those of similar coastal environments such as Long Island Sound and Narragansett Bay. This observation agrees well with other observations. Buzzards Bay has lower concentrations of water column chlorophyll <u>a</u>, averaging 95 mg m⁻² (Turner 1989), and lower primary production, 106-350 g C m yr⁻¹ (Roman and Tenore 1978, Smayda 1989), than both Narragansett Bay and Long Island Sound. This suggests that Buzzards Bay is less productive than these two bays. A consequence is that the sediments of Buzzards Bay presumably receive lower loadings of organic matter than these other systems.

It is important to point out that relative to these other areas, Buzzards Bay appears to be more efficient at recycling the nitrogen that is deposited on the sediments back to the overlying water (i.e., it loses less nitrogen through denitrification). This observation suggests that, although Buzzards Bay is currently less affected by eutrophication than many other coastal areas, it is difficult to predict how this ecosystem will respond to increased nitrogen loadings. There certainly is the potential for an increased primary production in response to nitrogen loadings which would undoubtedly lead to higher organic matter inputs to the sediments. However, it is unclear how the nitrogen cycling in Buzzards Bay sediments would be affected by increased loadings. It is possible that the sediments would remain as efficient as they are currently at recycling nitrogen back to the overlying water. On the other hand, Buzzards Bay sediments may behave more like those of other areas when they experience increased loading and become less efficient at returning nitrogen back to the overlying water. The former case suggests that Buzzards Bay could be quite susceptible to eutrophication, while the later case suggests that the sediments may serve to buffer or ameliorate to some extent the effects of eutrophication in Buzzards Bay. To fully address the concerns of managers about the susceptibility of Buzzards Bay to eutrophication it

would be useful know how the nitrogen cycling of these sediments would respond to increased organic matter inputs. One approach we are currently using is to test the response of benthic respiration and nitrogen cycling rates for Buzzards Bay sediments to increased organic matter loadings in laboratory experiments.

Some of the results from this study are useful for interpreting the applicability of some of the approaches or tools available to managers who are trying to assess the eutrophication of an environment such as Buzzards Bay. One class of useful tools are models which predict rates of benthic respiration and DIN release from sediments of potentially impacted environments. Many of these models make their predictions of these ecosystem level processes based on water temperature (for example, DiToro et al. 1989). Our results suggest that while this type of modelling approach would be adequate for Buzzards Bay for much of the year, these models might seriously underestimate benthic respiration during the spring when benthic fluxes were decoupled from water temperature. It would be important that such deviations from a temperature driven process be included in any modelling effort of Buzzards Bay benthic fluxes. Our results would further suggest that such models would be greatly improved if they incorporated a variable or measure that indicated the flux of algal detritus to the sediments. We were able to see this somewhat with our sedimentary pigment data, but some other measure such as sedimentation rate or water column productivity might also provide the necessary information. The main point is that any model that is going to accurately predict benthic fluxes will have take into account the amounts and timing of organic matter inputs to the sediment.

Another approach used in management efforts to assess the effects of eutrophication on an entire ecosystems such as Buzzards Bay is to make surveys of easily measured "state" parameters that are correlated to, and thus indicative of, more difficultly measured processes which are actually of interest. A common example is the use of water column chlorophyll a concentration as a surrogate for primary production. It would be desirable to have similar surrogate variables that one could use to assess the rates of benthic fluxes in Buzzards Bay. However, our data suggest that sedimentary carbon and nitrogen content as well as macrofaunal abundances are not likely to be very useful for predicting benthic fluxes even though these parameters can be surveyed over a wide range of areas for Buzzards Bay. Sedimentary pigment concentrations might be more useful, but even these parameters were not correlated to fluxes when we surveyed twelve stations in Buzzards Bay during August 1989. If it is desirable for the managers interested in monitoring for the effects of eutrophication in Buzzards Bay to have such survey parameters for benthic processes then future research will be required to come up with good indicator parameters for Buzzards Bay. It is worth noting that a remotely deployed camera system such as the REMOTS^(R) system used by Science Applications International Corporation, which integrates several visually derived parameters (Rhoads and Germano 1988), may help accomplish this goal in many management situations, however, there was no apparent relationship between the benthic fluxes we measured during August 1989 and the OSI (Organism-Sediment Index - the integrated parameter calculated from REMOTS^(R) data) determined in April 1987 for five stations of the transect away from the New Bedford sewage outfall (Fig. 1). Obviously,

this comparison between the two studies does not constitute any conclusive test of the usefulness of REMOTS^(R) for predicting benthic fluxes given the number of years that separate the two studies and the different seasons in which the measurements were made; more tests, with simultaneous measurements of both benthic fluxes and OSI, are necessary.

Another approach of interest in terms of the eutrophication of Buzzards Bay is to attempt to use historical data to assess whether there have been changes in the structure of the Buzzards Bay ecosystem. As discussed earlier, we can compare our data on the benthic animal communities in Buzzards Bay to those of Sanders (1958, 1960) collected in the 1950's. In general, our data agree with that of Whitlach (pers. comm.) and show significantly higher numbers of benthic animals in the muddy portions of Buzzards Bay than found by Sanders (1958, 1960). We also support Whitlach's observation that Mediomastus, a small polychaete, is currently a dominant member of the benthic community; Mediomastus was only reported by Sanders (1958, 1960) as a small Capitellid polychaete of minor importance. However, as Whitlach pointed out, it is difficult at this point to determine whether these differences are actually due to changes in the benthic communities in Buzzards Bay or simply due to improved methods for sorting and quantifying benthic organisms. Other than the possible increase in relative abundance of Mediomastus, there appears to have been little change in the structure of the benthic community of Buzzards Bay since the 1950's; it appears that the benthic community structure of Buzzards Bay has been fairly stable over the past thirty years. Although we can not definitively answer whether there have been any long-term changes in the benthic animal community of Buzzards Bay, it would probably be useful

to survey the benthic macrofauna in several fixed stations every decade or so with standardized techniques to look for slow changes in Buzzards Bay's eutrophication status. This type of long-term and standardized monitoring data could be quite useful in assessing the decade scale changes, of both natural and anthropogenic origins, that may occur in the future of Buzzards Bay.

In conclusion, benthic respiration and DIN release are ecosystem-level processes that reflect the interrelationships between processes occurring within the water column (e.g., primary production) and processes occurring within the sediments (e.g., organic matter decomposition). These benthic flux rates are indicative of the delivery of organic matter to the sediment and play a significant role in the cycling of nutrients, specifically nitrogen, in the coastal environment. Thus, monitoring these benthic processes give us insight into the rates of material cycling and nutrient loading within an environment such as Buzzards Bay. Furthermore, understanding the factors which control these processes, such as temperature and organic matter loading, helps us assess both the current status of Buzzards Bay as well as how this environment will respond to future perturbations.

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Yoshida, Y., and M. Kimata. 1969. Studies on the marine microorganisms utilizing inorganic nitrogen compounds-IV. On the liberation rates of inorganic nitrogen compounds from bottom muds to sea water. Bull. of Jap. Soc. Sci. Fish. 35:303-306. Table 1. Annual oxygen consumption, carbon oxidation, DIN release and denitrification budget for September 1988- September 1989 at the Weepecket Island Station. The oxygen consumption and DIN release values are calculated as the area under the curves in Fig. 2. The reduced sulfur burial calculation is based on the range of sedimentation rates $(0.05-0.3 \text{ cm yr}^{-1})$ reported in McNichol et al. 1986 and a range of reduced S concentrations $(130-240 \ \mu\text{mol} \ \text{S} \ \text{cm}^{-3})$ for sediment depths greater than 10 cm measured at this site during 1984 and 1985 (Hobbie et al., unpub. data). The amount of carbon oxidized was assumed to be 1 mole for every mole of oxygen consumed or 2 moles for every mole of reduced sulfur buried. The denitrification estimate is based on the assumption that the observed O/N ratio is greater than 13.25 due nitrogen that has been lost from the system through denitrification. See text for further discussion.

5210 mmol m ⁻² yr ⁻¹ 63 g C m ⁻² yr ⁻¹)
130-1440 mmol m ⁻² yr ⁻¹ 1.6-17.3 g C m ⁻² yr ⁻¹)
64.6-80.3 g C m ⁻² yr ⁻¹
686 mmol m ⁻² yr ⁻¹ 15.19 12.8%

Table 2. Benthic respiration and dissolved inorganic nitrogen (DIN) flux measurements from Buzzards Bay (A) and other coastal marine systems (B).

Site	Months	Гетрегаture °С	Benthic Respiration moles $O_2 m^{-2} d^{-1}$	Nitrogen Flux (ΣDIN) mmoles N m ⁻² d ⁻¹	O/N Ratio
A) Burgards Bay MA ¹	Ian Nov	2.16	11 1 44 0	0.20-3.00	28-46
Buzzards Bay, MA	Jan - Nov	2-10	50 00	0.29-3.00	20-40
Buzzards Bay, MA	Aug		38.90		
Eel Pond, MA [*]	July	20	33.60	2.04	32
B)					
Narragansett Bay, RI ³	Jan - Dec	0-24	7.5-112.5	0-9.6	27-33
Long Island Sound, CT ⁴	Mar - Nov	4-22		-1.0-8.0	
New York Bight, NY ⁵	Aug		26.4	0.60	87
Patuxent Estuary, MD ⁶	June - Aug		94.8	17.04	26
South River Estuary, NC ⁷	Jan - Dec	1-25	19.8-75.6	0-6.55	31
Neuse River Estuary, NC ⁷	Jan - Dec	1-25	19.6-51.8	0-11.05	13.5
Georgia Bight, GA ⁸	July	28	90.6	4.20	22
La Jolla, CA ⁹	June - Aug	11-24		0.96	
Kaneohe Bay, HI ¹⁰	Jan - Dec		14.4	1.3	20
Lock Ewe Estuary, Scotland ¹¹	June - July	6-13	19.2-37.2	0.48-1.92	55
Vostock Bay, USSR ¹²	Aug		33.6	3.60	19
Maizura Bay, Japan ¹³	July	18-30		0.31-0.77	

Studies:

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1. Rowe et al. 1975

3. Nixon et al. 1976

5. Rowe et al. 1976

7. Fisher et al. 1982

9. Hartwig 1975

11. Davies 1975

13. Yoshida and Kimata 1969

2. Smith et al. 1973

4. Aller and Benninger 1981

6. Kemp and Boynton 1979

8. Hopkinson and Wetzel 1982

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10. Smith 1978

12. Propp et al. 1981

Table 3. Rank order abundance of the most common macrofaunal taxa in the muddy bottom regions of Buzzards Bay. Species names are underlined while other taxa are identified to family. The five most common animals in each study are listed as well as the rankings of those animals in the other studies, even when uncommon.

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Таха	Our Study (1988-89)	Whitlach's Study (1975-76)	Sanders' Study (1955-58)
Nucula appulata	1	1	1
<u>Nucura amurata</u>	1	1	
<u>Mediomastus</u> <u>ambiseta</u>	2	2	(rare)
Paraonid polychaetes	3	3	(rare)
Cylichna oryza	4	7	3
Nephtys incisa	`5	5	2
Spionid polychaetes	9	4	7
Lumbrenerid polychaetes	6	6	4
Pyramellid gastropods	10	9	5

Table 4. The results of the multiple regression and path analyses to predict benchic flux rates at the Weepecket Island site based on temperature and sediment characteristics. The amount of variation explained (R^2) by the final statistical model, as well as for each of the explanitory variables alone, is given for benchic respiration and DIN release rates. See text for explanation of how the final models were derived and which sediment parameters were tested.

BENTHIC RESPIRATION

EXPLANITORY VARIABLE	<u>R²</u>
Temperature (Q ₁₀ =1.89) Chlorophyll	41.6% 6.6%
Temp. and Chlor. combined	77.4%

DIN RELEASE

EXPLANITORY VARIABLE	<u>R²</u>
Temperature (Q ₁₀ =1.63) Phaeopigments	85.3% 8.7%
Temp. and Phaeo. combined	91.8%

	Benthic Respiration	DIN Release	C Content	N Content	Cholorphyll Concentration	Phaeopigment Concentration
Benthic Respiration						
DIN Release	0.86*					
C Content	-0.20	-0.17				
N Content	-0.29	-0.23	0.98*			
Cholophyll Conc.	-0.19	-0.15	0.73*	0.71*		
Phaeopigment Conc.	-0.05	-0.29	0.50	0.46	0.15	
Benthic Animals	0.19	0.28	0.12	0.03	-0.11	0.31

Table 5. Correlation matrix between benthic fluxes, sediment parameters and benthic animal abundances for measurements made during August 1989 at twelve stations in Buzzards Bay. Correlations significant at $p \le 0.05$ are indicated with an asterix (*).

FIGURE LEGENDS

- Figure 1. Stations sampled in Buzzards Bay. The Weepecket Island Station was the site of our seasonal measurements. The lettered stations (G-R) are the same as described by Sanders (1958). The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R.
- Figure 2. Seasonal pattern of benthic fluxes at the Weepecket Island site. A) Benthic respiration rates. B) Dissolved inorganic nitrogen (DIN) release rates. All flux values are reported as mean <u>+</u> standard error of rates determined from 3-4 replicate cores. In both panels the water temperature is indicated by the dashed line.
- Figure 3. Benthic fluxes at several locations in Buzzards Bay during August 1989. A) Benthic respiration rates. B) Dissolved inorganic nitrogen (DIN) release rates. The Weepecket Island Station is indicated as WEEP. The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R. Sanders' (1958) stations are indicated by letters G-R. All flux values are reported as mean <u>+</u> standard error of rates determined from 3-4 replicate cores.
- Figure 4. Seasonal pattern of the ratio of benthic respiration rate to DIN release rate (O/N ratio) at the Weepecket Island Station.
- Figure 5. O/N flux ratio of benthic fluxes for stations in Buzzards Bay measured during August 1989. The Weepecket Island Station is indicated as WEEP. The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R. Sanders' (1958) stations are indicated by letters G-R.
- Figure 6. Profiles of sediment carbon and concentration from four representative times of the year during 1989 at the Weepecket Island Station. The data are presented as percent of dry sediment and each value represents the mean <u>+</u> standard error of replicate (2) cores collected from the site.
- Figure 7. Integrated carbon (A) and nitrogen (B) concentrations at the Weepecket Island site during 1989. Integrated concentrations are the sum of the carbon or nitrogen concentrations for the top 5 cm but expressed on an areal basis. Values are the mean <u>+</u> standard error of replicate (2) cores collected at each sampling period from the site.
- Figure 8. Profiles of carbon to nitrogen ratio of the sediment from four representative times of the year during 1989 at the Weepecket Island Station. The data are ratio between the carbon and nitrogen concentrations for each depth and each value represents the mean \pm standard error of replicate (2) cores collected from the site.
- Figure 9. Profiles of sediment carbon and concentration from the twelve stations sampled during August 1989. The data are presented as percent of dry sediment and each value represents the mean <u>+</u> standard error of replicate (2) cores collected from each site. The Weepecket Island

Station is indicated as WEEP. The lettered stations (G-R) are the same as described by Sanders (1958). The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R.

- Figure 10. Profiles of carbon to nitrogen ratio of the sediment from the twelve stations sampled during August 1989. The data are ratio between the carbon and nitrogen concentrations for each depth and each value represents the mean \pm standard error of replicate (2) cores collected from each site. The Weepecket Island Station is indicated as WEEP. The lettered stations (G-R) are the same as described by Sanders (1958). The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R.
- Figure 11. Profiles of sediment phytoplankton pigment concentrations from four representative times of the year during 1989 at the Weepecket Island Station. Total pigment concentration is calculated as the sum of chlorophyll <u>a</u> (Chlor. <u>a</u>) and phaeopigments (Phaeo.). The data are presented as μ g pigments per cubic cm of sediment and each value represents the mean <u>+</u> standard error of replicate (2) cores collected from the site.
- Figure 12. Integrated phytoplankton pigment concentrations at the Weepecket Island site during 1989. Integrated concentrations are the sum of the chlorophyll <u>a</u>, phaeopigment (Phaeo.) and total pigment concentrations for the top 5 cm but expressed on an areal basis as mg pigment m⁻². Values are the mean <u>+</u> standard error of replicate (2) cores collected at each sampling period from the site.
- Figure 13. Profiles of sediment phytoplankton pigment concentrations from the twelve stations sampled during August 1989. Total pigment concentration is calculated as the sum of chlorophyll <u>a</u> (Chlor. <u>a</u>) and phaeopigments (Phaeo.). The data are presented as μ g pigments per cubic cm of sediment and each value represents the mean <u>+</u> standard error of replicate (2) cores collected from the site. The Weepecket Island Station is indicated as WEEP. The lettered stations (G-R) are the same as described by Sanders (1958). The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R.
- Figure 14. Integrated phytoplankton pigment concentrations for the twelve stations sampled during August 1989. Integrated concentrations are the sum of the chlorophyll <u>a</u>, phaeopigment (Phaeo.) and total pigment concentrations for the top 5 cm but expressed on an areal basis as mg pigment m^{-2} . The integrated total pigment concentration is given by the height of the combined bar for each station. Values are the mean <u>±</u> standard error of replicate (2) cores collected at each sampling period from the site. The Weepecket Island Station is indicated as WEEP. The lettered stations (G-R) are the same as described by Sanders (1958). The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R.
- Figure 15. Total macrofaunal abundances at the Weepecket Island site during 1988 and 1989. Values are the mean \pm standard error of 2-3 replicate cores collected at each sampling period from the site.

- Figure 16. Total macrofaunal abundances at twelve stations sampled during August 1989. Values are the mean <u>+</u> standard error of 2 replicate cores collected at each sampling period from the site. The Weepecket Island Station is indicated as WEEP. The lettered stations (G-R) are the same as described by Sanders (1958). The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R.
- Figure 17. Abundances of the most common macrofaunal taxa at the Weepecket Island site during 1988 and 1989. Densities of the two common molluscs are given in the upper panel (A), of the three most common polychaetes in the middle panel (B) and of all other taxa in the lower panel (C). Values are the mean ± standard error of 2-3 replicate cores collected at each sampling period from the site.
- Figure 18. Abundances of the common macrofaunal taxa at the twelve stations sampled during August 1989. The mean densities for each of the macrofaunal groups (as specified in Fig. 17) from 2 replicate cores collected at each site are represented by the thickness of differently shaded regions of each bar. The total macrofaunal density for each station is given by the eight of each bar. The Weepecket Island Station is indicated as WEEP. The lettered stations (G-R) are the same as described by Sanders (1958). The New Bedford REMOTS^(R) transect is represented by Stations 7-14 and Station R.

5.



Weepecket Station Benthic Fluxes







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Weepecket Island Station

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Station





Sediment C:N Ratio Weepecket Island Site















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Weepecket Island Site Total Macrofauna

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Haminoea Spionidae



Other Species

Appendix I. LORAN-C Coordinates for the stations we sampled in Buzzards Bay during 1988-1989.

E. C.

Station	Date	LORAN-C	Coordinates	(TD's)
Weepecket	May 25, 1988		25475.6	43958.2
Island	August 12, 1988	14165.0		43958.0
·	September 27, 1988	14165.0	25475.5	
	December 19, 1988	14163.0	25472.8	43958.0
	March 16, 1989	14166.4		43957.6
	May 4, 1989	14166.7		43956.8
	May 25, 1989	14166.4		43957.0
	June 16, 1989	14166.1		43957.0
	July 19, 1989	14166.2		43957.2
	August 15, 1989	14166.4		43956.9
	September 11, 1989	14166.3		43956.9
7	August 15, 1989	14208.0		43984.6
10	August 1, 1989	14220.8		43969.9
11	August 1, 1989	14218.4		43966.8
14	August 1, 1989	14221.4		43957.7
G	August 8, 1989	14146.1		43973.3
Н	August 8, 1989	14156.6		43978.9
К	August 8, 1989	14152.0		43963.6
L	August 8, 1989	14168.0		43969.6
М	August 15, 1989	14183.2		43973.5
Q	August 15, 1989	14208.0		43984.6
R	August 1, 1989	14221.4		43956.1

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