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Anthropogenic modification of the Israeli Mediterranean coast, tracked by live-dead benthic foraminifera assemblages

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ABSTRACT

Increased nutrient input into the ultra-oligotrophic eastern Mediterranean can be monitored using benthic foraminifera, well established environmental bio-indicators. The Shafdan Wastewater Treatment Plant is the largest point source of pollutants on the Israeli shoreline, discharging activated sludge about 5 km offshore of Palmachim. A 2003-4 study found that living benthic foraminifera assemblages respond to organic overload input, dispersion and aeration, at sub-seasonal time-scales. The present research was aimed at tracking the long-term environmental impact over the past ~10 years, near the outfall (PL3), and at 5.5 and 7 km (PL29 and PL64 respectively), using comparison of living vs. dead benthic foraminiferal assemblages correlated against measured environmental parameters. Living (Rose-Bengal stained) assemblages from the upper 5 cm, and time-averaged dead benthic foraminifera from the top 2 cm were sampled at all sites in January, May, July and November 2012, together with data on environmental parameters.

The sampling year of 2012 was extremely stormy with a strong current regime all year long, and high frequency of deep mixing events, reflected in lower TOC and Chl a concentrations compared to 2003-4. Living foraminifera showed considerable sensitivity to organic enrichment, by reduced numerical abundance and species richness in the most polluted station, while in the more remote stations, both parameters were significantly higher. When compared to 2003-4, the reduced abundance shows long term damage to the foraminiferal community caused by the ongoing discharge of sewage sludge. The short term improvement in diversity measures in the remote station is likely caused by the highly stormy year.

Species composition of the dead assemblages in all three stations were similar but the numerical abundance in station PL3 showed a seasonal pattern not found in the two remote stations. The dead assemblage is more similar to the live one in the remote stations, while near the outfall at PL3 the dead assemblage is still imprinted with pre-disturbance residual species. Thus, the results of this study demonstrate the great potential of foraminiferal live-dead fidelity to serve as a sensitive model system to predict future response to level of anthropogenic stress.

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1. INTRODUCTION

1.1. Background

Urbanization along coastal areas severely influence the local environment, increasing air pollution due to industrial development and fossil fuel consumption, water contamination due to marine fish farming, agriculture runoff or sewage treatment (Freedman, 1995; Verhoeven et al., 2006) . Human impact is reflected in the aquatic environment by primary production acceleration (eutrophication), a widespread problem extending all over the globe e.g. Baltic Sea, North Atlantic Ocean, Osaka Bay (Japan), Gulf of Mexico, Chesapeake Bay estuary (North America), southeast China etc. (Rosenberg, 1985; Howarth et al. 1996; Rabalais et al., 1996; Boesch, 2002; Norse, 2005; Tsujimoto et al., 2006). Eutrophication is caused by nutrient overload, especially of phosphates and nitrates, that can result in water degradation (Paerl, 1995; Smith et al., 1999; Rabalais, 2002) with extensive environmental and economic implications, e.g. algal blooms, oxygen consumption, loss of habitat, loss of biodiversity and decreasing fish resources (Carpenter et al., 1998; Rabalais, 2002). Nixon (1995) established a simple trophic classification for marine systems, concluding that <100 gCm^{-2} yr^{-1} is considered oligotrophic.

The Mediterranean has been considered one of the most oligotrophic seas around the globe (Azov, 1991; Turley, 1999). It is a semi-enclosed basin open to the Atlantic Ocean to the west through the narrow Straits of Gibraltar. Oceanic circulation occurs in an anticlockwise direction around the Mediterranean basin over a period of 80-100 years (Turley, 1999). Results of a recent 6-year study from 1999-2004 based on satellite observations and in situ measurements in the Mediterranean showed a primary production gradient decreasing eastward, ranging on average from >250 gCm^{-2} yr^{-1} in the Alboran Sea to <80 gCm^{-2} yr^{-1} in the Levantine Basin (Lazzari et al., 2012) with localized nutrient overload mainly caused by marine fish farming, agriculture runoff or sewage treatment plants (Carstensen et al., 2001).

Benthic foraminifera can be found in almost any aquatic environment, from brackish to hypersaline water, at depths ranging between beach-rocks of ~1m down to abyssal depths of more than 10 km (e.g. Almogi-Labin et al., 1992; Hayward & Hollis, 1994; Todo et al., 2005; Arieli et al., 2011). They are also traditionally known for their spectacular fossil record (Sen Gupta, 1999; Murray, 2006). In the last few years, there is a growing interest in foraminiferal bio-monitoring (e.g. Frontalini & Coccioni, 2011; Schönfeld et al., 2012). Their fossil assemblages in an anthropogenic altered environment

can serve as a “pre-impact faunas” where no environmental baseline study has been carried out prior to alteration (Schönfeld et al., 2012).

The Israeli shoreline is located on the southeast margin of the Levantine basin, in the SE corner of the Mediterranean. The main source of sediment input was the Nile River in Egypt. In the last few decades most sediments are the product of Egypt's Nile delta erosion. Nile sediments are transported along the coast to Israel from the south to north (Emery and Neev, 1960). Sediment rates calculated for the Mediterranean at 35-50 meters water depth show a rate of accumulation of ~2mm/year, decreasing northward (Almogi-Labin et al., 2009). In the past, high accumulation rates characterized the continental slope of Israel, but fell at the time of damming of the Nile River in 1965 (Stanley, 1988), sharply reducing also fresh water and nutrient inputs (e.g. Inman and Jenkins, 1984; Krom et al., 1991). Extremely low nutrient concentrations were measured in the photic zone (Krom et al., 1991), causing low productivity of about ~45 gC/m^2/year (Herut et al., 2000). These rates are considered ultra-oligotrophic (Berman et al., 1984; Krom et al., 1991; Yacobi et al., 1995). Over the past 5000 years marine productivity (and nutrient flux) were relatively low, as a result of the arid climate (Tapiero, 2002) decreasing further since the damming of the Nile in the last century.

In this study we estimate the long-term effect of localized organic material enrichment on the foraminiferal assemblage. For that purpose we compared the living community found in 2012 with living assemblages of 10 years earlier, described by Hyams-Kaphzan et al., 2009. In addition, we compared assemblage composition between living and dead benthic foraminifera, so as to test its utility as a proxy for recent ecological shifts. To date, there has been no study investigating how well the foraminiferal death assemblage reflects the living assemblage composition in the eastern Mediterranean basin, despite the long-term changes in Nile river input.

1.2. The Mediterranean continental shelf

The Levant coast of Israel extends 180 km in a nearly straight line trending NE-NNE. In the eastern Mediterranean, the surface water layer (0-40 m) is characterized by high salinity (>38.7 psu) and temperature range of 17 °C for winter and up to 30 °C in summer (Hyams-Kaphzan et al., 2009). The upper 120 m of the water column is well mixed in winter (December–March), while in the summer, the 25 m mixed surface layer is underlain by a sharp halocline and thermocline (Herut et al., 2000).

Wave- and wind-induced long-shore currents drive sediments predominantly from south to north (Emery and Neev, 1960; Golik, 1993; Zvieli et al., 2007). The average velocity of these northwards currents is less than 15 cm/s, decreasing with increasing depth in summer, and increasing in winter to events reaching 90 cm/s (Rosentraub, 1990; Rosentraub and Brenner, 2007). The bulk of the sediments are siliciclastics originating from the Nile River delta, with a small contribution from local sources.

1.3. Shafdan plant and monitoring activated sludge effects

Urbanization of the Israel coastal plain has affected the littoral environment by nutrient influx via direct wastewater outfalls, surface run-off and atmospheric deposition (Carstensen et al., 2001). The largest point source of pollution since 1987 is the Dan Region Wastewater Treatment Plant (Shafdan) offshore of Palmachim, with an output of 15,000 m^3 / day of activated sewage sludge (biosolids after secondary treatment). The sludge is piped to an outfall about 5 km from the shoreline at 38 m water depth. The activated sludge consists mostly of microbiological mass, with some heavy metals and other toxic material (~1% dry weight).

Studies of macrobenthic communities showed that the outfall area was unpolluted prior to 1978 (Galil and Lewinsohn, 1981). Since 1992, a long-term monitoring study of water chemistry and macrobenthic variability was carried out by Israel Oceanographic and Limnological Research (IOLR-Haifa). Monitoring was conducted during spring and fall on even-numbered years, and during fall on odd-numbered years, to assess the impact of sludge injection on the ultra-oligotrophic background. The record shows seasonally high levels of organic material, high heavy metal concentration, and changes in benthic biota (increase of polychaete worms), up to 4 km NE of the outfall (Kress et al., 2004) . Strong current activity during winter causes mixing of the water column and efficient sludge dispersal, so that in spring, relatively diverse benthic populations were found. In the summer and autumn more gentle currents allow sludge to accumulate and organic matter concentration to increase, with the result that the area near the outlet became sterile (Kress et al., 2004, 2013).

A detailed study of the living foraminiferal assemblages in the vicinity of the Shafdan outfall was conducted by Hyams-Kaphzan et al. (2009). Two stations (PL3 and PL29) were examined bi-monthly from January 2003 to May 2004. Levels of eutrophication were based on Chlorophyll *a* (Chl *a*), total organic carbon (TOC) and O_2

concentrations in the sediment. Polychaete worms were studied in addition to the benthic foraminifera (Hyams, 2006). The two sampling stations showed great variation in their sediment properties. The sediments at PL29 were light to dark brown silty to muddy sand with ~12% $CaCO_3$. They were easily distinguished from station PL3, where the sediments were fluffy and dark-colored from added sludge, and carbonate content was at times as low as ~2%. Although sludge was undetected in early winter and spring, the sediment remained darker and grayer than at PL29. Mean grain size varied from summer to winter, from 32.5 - 49 μm at PL29 and 10.7 - 51.3 μm at PL3 according to currents intensity. Chl *a* reached 11.6 μg/g at PL3, up to 7 times higher than for PL29, and organic carbon varied to a maximum of 15 wt.% at PL3, compared with 1 wt.% at PL29. Bottom water O_2 concentration was high at both sites in winter and low in summer. It was theorized that site PL29 represents relatively clean, oligotrophic waters, typical of the eastern Mediterranean shelf with highest Chl *a* and TOC values in spring and summer, and no sludge was seen on sediments from this station. PL3 is located directly within the outfall plume, where sludge is injected continuously. Sludge is removed in winter by storms, and in spring by biotic consumption. The sediment is highly eutrophic especially during summer and fall, and Chl *a* and TOC values can be high due to nutrients from injected sludge. Bottom water O_2 and in-sediment penetration (to 9 mm) is highest at both sites in the winter. In the years 2007-2009 the IOLR monitoring detected an extension of the affected area up to 7 km to the NE (Kress et al., 2009), as far as station PL29, that was until then considered a clean control site (Kress et al., 2004). Furthermore a change in the seasonality pattern of activated sewage sludge accumulation was found, with similar sediment quality (mainly organic matter) in the affected area in both seasons (Kress et al., 2009). However, in 2010 and to a higher extent in 2011-12 the seasonal pattern was reestablished (Kress et al., 2013).

1.4. Foraminifera as environmental bioindicators

Benthic foraminifera are well established environmental bio-indicators (e.g. Debenay et al., 1990; Barmawidjaja et al., 1992; Alve, 1995; Osterman et al., 2008). Their distribution pattern has long been studied in marine environments polluted by high organic load (e.g. Watkins, 1961; Bandy et al., 1964, 1965). If the background was originally oligotrophic, the modification of the natural assemblage is better pronounced (e.g., Alve, 1995; Schafer, 2000; Mojtahid et al., 2008) but where the background is

mesotrophic, change may not be well marked. Bates and Spencer (1979) and Stott et al. (1996) reported increased foraminiferal abundances at sewage outfalls due to increased food resources and reduced predation and competition. On the other hand extreme excess of organic matter close to the outfall can lead to oxygen depletion, causing reduction in abundance and number of species (e.g. Schafer, 2000).

Some recent studies of dead benthic foraminifera of the Levant shelf followed N-S and E-W transects, with cores penetrating the Holocene and the last 2 glacial stages of the Pleistocene (Tapiero, 2002; Avital, 2002; Lazar, 2007; Hyams-Kaphzan et al., 2008). Benthic foraminifera were found to be abundant, diverse (>350 species!), well preserved in the record and sensitive to changing environment conditions (Hyams-Kaphzan et al., 2008). On the other hand, the eutrophication gradient off the Shafdan outfall affected living benthic foraminifera, with strong variability in their total standing stocks (TSS), species richness, in-sediment living depth and species composition (Hyams-Kaphzan et al., 2009). The relatively oligotrophic site PL29, had an abundant, diverse benthic foraminiferal assemblage living to 10 cm in sediment depth, while at the eutrophic site PL3, foraminiferal abundances were lower by an order of magnitude, living mostly at the upper surface layer, as a reaction to O_2- depletion stress downcore. At PL29 the standing stocks of foraminifera peaked in summer (September) following the natural Chl α cycle, which itself responded to warmer temperatures by proliferation of producing organisms. At this site, foraminiferal TSS were more sensitive to food resources than to O_2 concentration. At PL3, the TSS peaked in winter and spring (January and May) when sludge is dispersed by storms and bioturbation, while living foraminifera were absent when sludge accumulated up to 9 cm in the sediment and anoxia occurred during fall (November). However, in the oligotrophic Eastern Mediterranean, foraminifera do not use the sludge as labile food; they are more sensitive to the increased nutrients, following the Chl α cycle and less importantly, oxygen concentration. In general, the two sampling sites shared a common pool of species, among which the opportunist *Ammonia tepida* was highly dominant. However, many rare species occurred at PL29 but were absent at PL3. Benthic foraminifera were therefore found to be sensitive to trophic changes, responding on sub-seasonal time-scales, and indirectly tracked the injection and dispersal of organic loads on the shelf by the utilization of nutrient by blooming of phytoplankton (Hyams-Kaphzan et al., 2009).

1.5. Live vs. dead foraminifera assemblages

The dead assemblage is composed of foraminiferal tests accumulated in the sediment over time. The assemblage composition depends on the reproduction rate of each species and on post mortem taphonomic effect such as transport, mechanical erosion, dissolution and bio-erosion (e.g. Murry, 2006, Schönfeld et al., 2012). The top few cm (sometimes as much as 1 meter) tends to be a mixed layer controlled by turnover rate, bioturbation and sedimentation rate that can represent decades or years (Martin, 1999). Short term events, seasonal and annual signals, as well as spatial differences become erased in a process termed "time averaging". The amount of erasing depends on the thickness of the mixed layer and the sedimentation rate (Martin, 1999). The sedimentation rate tends to be higher in the vicinity of natural major nutrient suppliers (e.g. rivers or deltas) as predicted also for sewage outfall such as Shafdan.

Dead assemblages were frequently used as a restoration baseline in order to reconstruct palaeoecological conditions when no natural environment was found nearby (Murray, 2006). Mismatch between live and dead assemblages tends to be higher in anthropogenic altered sites. By using molluscan assemblages, Kidwell (2007) showed that live-dead agreement is significantly lower in documented anthropogenic eutrophication settings compared with areas of negligible human impact, based on 72 mollusk-based data sets. Low live-dead agreement often relates to anthropogenic impact as a result of species redundancy in the living community, sometime accompanied by new species entrance (Kidwell, 2013). Several studies engaged foraminiferal live-dead agreement, including Jorissen & Witteling (1999), Edelman-Furstenberg et al. (2001), Gooday & Hughes, (2002) etc., attempting also to estimate preservation potential. However, the knowledge is sparse and strict comparison between live-dead assemblages in natural and anthropogenically altered areas as conducted on mollusks by Kidwell (2007) has not been done yet for foraminiferal assemblages.

1.6. Research objectives

(1) To reexamine the impact of high organic flux on living foraminifera in control stations (PL29 and PL64) vs. polluted station (PL3) over four seasons.

(2) To track recent changes over the past ~10 years of the living foraminiferal assemblages in two stations PL3 and PL29 based on comparison to live foraminifera data collected from January 2003 to May 2004 (Hyams-Kaphzan et al., 2009), and establish the long term influence of environmental parameters changes on those assemblages.

(3) To establish the impact of high organic flux on dead foraminifera in the top 2 cm of sediment as reflected in test preservation and erasure of short term events as part of the time-averaging process, in control (PL29 and PL64) vs. polluted (PL3) stations.

(4) To perform a detailed multivariate statistical analysis of the live and dead assemblage community structure, and to establish the environmental parameters of clean vs. polluted sampling stations within and between habitats and across seasons.

(5) To test for significant match or mismatch in the composition of live and dead assemblages as a signal of anthropogenic impact, aimed at using them as a proxy for inner-shelf environmental health.

2. MATERIAL AND METHODS

2.1. Sampling procedure

Three stations (PL3, PL29, PL64) were sampled by the R/V Etziona for benthic foraminifera, water column and sediment properties, aimed at tracking the productivity gradient from eutrophic to ultra-oligotrophic (Appendix). Two stations (PL3, PL29) were sampled seasonally (January, May, July, November 2012), while a third station (PL64) was sampled twice (May, November 2012). The three stations are located off the Palmachim shoreline (Figure 2.1) at 36 m water depth. PL3, the most highly eutrophic station is situated 200 m north of Shafdan outfall. PL29 is located 5.5 km north of the activated sewage sludge outfall, and is now regarded as mesotropic to oligotrophic. PL64 is located 7 km north to the activated sewage sludge outfall, and is now considered the ultra-oligotrophic control site (Table 2.1). Choice of those stations followed long-term monitoring studies conducted since 1992 by Kress et al. (2004, 2009) and Hyams-Kaphzan et al. (2009). Station PL64 was added as an oligotrophic control following conclusions of Kress et al. (2009) that the direct area of sludge influence extended at that time to include station PL29, while station PL64 was still consider uninfluenced control station.

Water column properties including temperature, salinity, dissolved oxygen, pH and turbidity profiles were measured on board using a CTD sampling device. The sediments at each sampling station were sampled three times using a box corer with surface area of 0.062 m^2 and an effective depth penetration of 50 cm.

For Chl a analysis from each box-corer, triplicate samples (ca. 1-2 g) were collected from the top 0-0.5 cm sediment layer, preserved in petri-dishes, covered with aluminum foil and frozen on board. The sediment from the first box-core was sampled three times using Perspex pipes (Ø=5.3 cm) for foraminifera, chemical and grain size analyses. Another two sediment samples were taken for foraminiferal analysis from the second and third box cores, giving a total of five short cores. The upper five cm from each core were sliced immediately on board into 1 cm thick layers (5 subsamples; Figure 2.2). The samples for benthic foraminifera were preserved in Rose Bengal solution (2 gr/L ethanol 95%; Figure 2.2). Sediments for chemical and grain size analyses were frozen immediately on board. The foraminiferal analysis in this study followed Hyams-Kaphzan et al. (2009) work protocol modified with FOBIMO (Foraminiferal Bio-Monitoring) initiative protocol (Schönfeld et al., 2012) as shown in Table 2.2. For practical reasons (time limitation) only two of the replicates (total of 10 subsamples) were analyzed, the third replicate was

added for all samples of station PL3 (total of 15 subsamples) when inconsistency between duplicate samples emerged (e.g. samples collected during January and May), or in order to increase number of specimens collected when less than 20 specimens per sample were found (e.g. samples collected during July and November).

2.2. Sedimentological analysis

All the 100 sediment samples for total organic carbon (TOC) and grain size analyses were lyophilized for optimal long-term preservation without changing the sediment properties. Grain size distribution was analyzed for obtaining the most frequently occurring grain-size (mode) before and after organic matter (OM) removal. For the removal of OM, 3 g of each sample of the upper 1 cm was mixed with 100 ml of NaOCl 3% and 200 ml of water, then shaken for 1 week, centrifuged, washed twice with distilled water and lyophilized again. From each sample (before and after OM removal) a 0.15-0.2 g was mixed with 20 ml distilled water and 2 drops of Na-hexametaphosphate solution 0.5% for dispersion of aggregates. The particle size distribution (before OM removal) performed by ANALYSETTE 22 MicroTec plus laser diffraction was carried out in the sedimentological laboratory of the Ben-Gurion University, Beer Sheva. Particle size distribution of samples from the upper 0-1 cm (after OM removal) performed by Malvern Mastersizer 2000 laser particle size analyzer was carried out in the Geochemical Laboratory of the Geological Survey of Israel, Jerusalem.

For the TOC analysis, aliquots of 300 μg of the lyophilized samples were treated with 100 ml of fresh concentrated HCl for 16 hours at room temperature in silver capsules within specially machined ceramic blocks in the glass desiccators, to remove carbonates. The samples were oven-dried at 60˚C for 1 hour after draining off the residual fluid. The total organic carbon (TOC) value was determined after combustion at 1700 ˚C in an elemental analyzer (1112 Flash EA, Thermo-Finnigan) interface to an Isotope Ratio Mass Spectrometer (EAIRMS Delta V Plus, Thermo Scientific). The TOC content was calibrated using high organic sediment standard OAS B-2151 (6.72%C, Elemental Microanalysis) with range of 10-60 μg carbon. Work procedure followed Gelman et al. (2012) based on dichromate method. The analyses were carried out in the Geochemical Laboratory of the Geological Survey of Israel, Jerusalem.

The frozen Chl a sediment samples were lyophilized for 48 hours, then dry-sieved. The < 250 μm size fraction was homogenized, weighed and extracted in 1 ml of 90%

acetone, shaken and centrifuged. The supernatant was transferred to a dark tube, and the pellet was resuspended in 2 ml of 90% acetone, shaken and centrifuged. The supernatant was kept with the first extract and treatment repeated until a colorless supernatant was formed. The clear supernatant was measured using a spectrophotometer (HP 8452A). The concentration of the pigment was calculated using published extinction coefficients (Stal et al. 1978; Rowan, 1989). The analyses were carried out in IOLR-Kinneret (with Dr. Yosef Yacobi).

2.3. **Benthic foraminiferal analysis**

120 sediment samples were collected, sub-sampled and stained in Rose Bengal in 2012 at the three sampling stations for living benthic foraminifera. After 14 days in Rose Bengal, the ethanol in the samples was replaced by water and the samples were oven-dried at 50 °C and weighed; this is the original sample weight. Each sample was then wet-sieved over a 63 µm mesh, dried and weighed again for sand fraction weight. The samples of the upper 2 cm of sediment were split using a Solister splitter, until a sample with 250-300 dead benthic foraminifera was reached. Complete sieved samples were then again sorted, for picking all live (Rose Bengal stained) benthic foraminifera. Overall, a total of 120 samples for living and 40 samples for dead foraminiferal species were examined (Table 2.1). Taxonomic identification was based on Loeblich and Tappan (1987, 1994); Cimerman and Langer (1991); Hottinger et al. (1993); Sgarrella and Moncharmont (1993); Jones (1994), Hyams (2000, 2006) and Milker and Schmiedl (2012).

2.4. **Database compilation**

In each sample the number of live (Rose Bengal stained) and dead specimens was normalized per 10cc following Hyams-Kaphzan et al. (2009) (Table 2.2) while for Live-Dead comparison all data was standardized. Species diversity was based on several parameters including: **Species richness (S)** – number of species per sample; **Margalef index (J')** - A diversity index, taking into account the number of species and number of individuals, calculated as $J'=(S-1)/\ln(n)$ (Magurran, 2004); **Pielou's Evenness index** – a diversity index representing the distribution of individuals among the different species, approaching 0 when one taxon includes most individuals, and increasing towards J'=1 when all taxa have similar numbers of individuals J'=H'/log S where
H'=-sum((n_i/n)ln(n_i/n))) (Pielou, 1969).

Average Living Depth (ALD) was calculated based on $ALD_5 = \frac{\sum_{i=1,x}(ni*Di)}{N}$, Where x = lower boundary of the deepest sample included in the calculation; ni = number of live (stained) specimens in interval; Di = midpoint of sample interval I; and N = total number of stained individuals for all levels (Jorissen & Wittling, 1999).

The comparison to 2003-4 living community was based on data collected from stations PL3 and PL29 by Hyams (2006). Sediment properties (Chl *a* and Total Organic Carbonate; TOC) taken from the top 1 cm of sediment, grain size distribution taken from a bulk 0-5 cm after organic matter (OM) removal compared to the grain size distribution of the upper 1 cm of the current study (after OM removal). Cumulative abundance curves were based on species rank according to decreasing abundance. For each species the percentage of total abundance of all species is plotted against the species rank. Benthic foraminifera total standing stock (TSS), and dominant species numerical abundance were calculated for 10cc (summed over 0-1 cm), while the *Bolivina* numerical abundance per 10 cc was summed over the top 5 cm of the sediment and relative abundance of each of the *Bolivina* species was calculated.

2.5. Statistical analysis

Multivariate analysis of the data was conducted using the package PRIMER v.6 of the Plymouth Marine Laboratory (Clarke & Warwick, 1994). Principal component analysis (PCA) was conducted In order to determine the relationship between environmental parameters and their effect on the variability of the samples (stations).

Taxonomic composition between assemblages was tested based on zero-adjusted Bray-Curtis similarity coefficient using Analysis of Similarities (ANOSIM), Hierarchical Scaling (cluster analysis) and Non-Metric Multidimensional Scaling (nMDS). The ANOSIM test was based on two-way nested analysis for the three stations and four seasons, when significant ($P<0.05$), a pairwise test for determining the main between-groups differences was conducted. Cluster analysis was based on "group average mode" combined with SIMPROF test at significant level of 5%. Non-metric multidimensional scaling (nMDS) was used to project the samples on a two dimensional plot based on the pairwise distances, stress value evaluates the deviation from the original ranked distances in the transition to two dimension plot. A stress value of <0.2 was common to all analysis as suggested by Clarke and Warwick (1994).

For correlation between environmental parameters and foraminiferal living assemblage two statistical tests were used based on Spearman rank correlation: BEST analysis uses Euclidean distance similarity coefficient in order to find the environmental combination with the “best fit” correlation to foraminiferal abundance and composition while distance-based linear model (disTLM) uses permutations rather than the restrictive Euclidean distance and normality assumptions, calculated the contribution of each parameter is graphical display by dbRDA as a two dimension plot.

In all environmental analysis (PCA, BEST, disTLM and dbRDA) each sample contains log-transformed normalized values of the environmental parameters of the bottom water column (Temperature (°C), Salinity (psu), O_2 (mg/l) and Chlorophyll *a* (Chl-water;µg/l)), and of the top sediment layer (total organic carbon (TOC; wt.%), mode grain size (after OM removal; µm) and Chl *a* (Chl -sediment; µg/g)). For all living community analysis replicate samples were pooled together (a necessity in case of extremely low number of living specimens obtained from individual replicates Schönfeld et al., 2012) and normalized to 10cc. only the top 0-1 and 1-2 cm of sediment were used for comparison (since in some samples live specimens were not found beyond this depth). The selection of species for the environmental parameters comparison (BEST, disTLM and dbRDA analysis) and selected species behavioral patterns nMDS was based on Similarity Percentage Analysis (SIMPER test) comparing the relative abundance of each species between assemblages in order to identify which species were responsible for differences between stations in living community; for this only the upper 1 cm was used. For the comparison to 2003 at station PL3 standardized pooled replicate samples containing >20 specimens were used while for station PL29 all samples of >100 specimens were used after square root transformation and standardization. For all dead foraminiferal assemblage analyses, all sediment samples (top 0-1 and 1-2 cm) were normalized to 10 cc. All analyses were based on numerical abundance of each foraminiferal species without transformation unless mentioned otherwise. For live-dead comparison, samples were summarized from the upper 5 cm for the living community and top 2 cm for the dead assemblage and standardized in order to compare assemblage composition without size differences affecting the results.

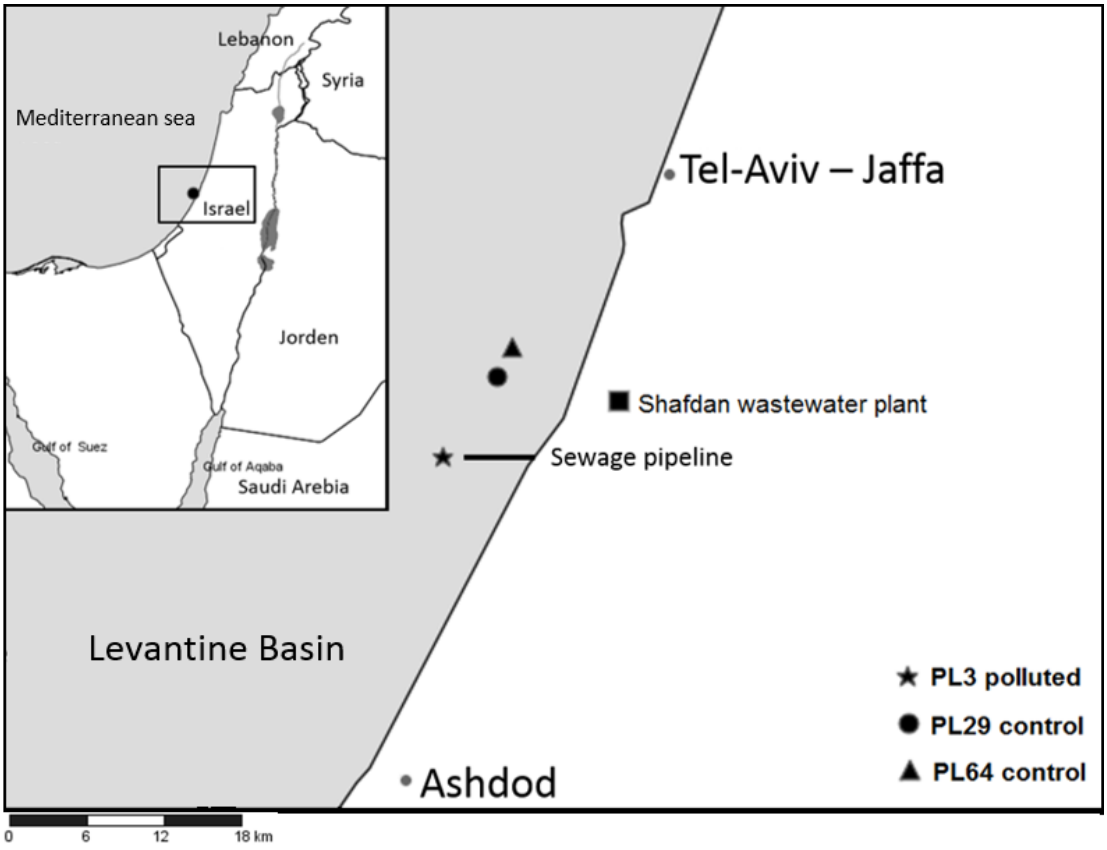


Figure 2.1: Map of Palmachim sampling stations: PL3 - eutrophic station, 200 m north of the outfall, PL29 – mesotrophic station, 5.5 km NE of the outfall, PL64 – oligotrophic station, 7 km NE of the outfall. (After Leshno Afriat, M.Sc. thesis, 2014).



Figure 2.2: Foraminifera sampling procedure: sediment core sliced into 5 samples of 1 cm layer each then preserved in Rose Bengal solution.

Table 2.1: Sampling campaign details			
Station	PL3	PL29	PL64
Location	31°55.90N 34°38.90E	31°58.40N 34°40.60E	31°59.40N 34°41.10E
Distance from outfall (km)	0.2	5.5	7
# of samplings/year	4	4	2
Core penetration depth (cm)	5	5	5
# of samples for Living foraminiferal analysis	4 seasons*5 cm *3 replicates = 60	4 seasons*5 cm *2 replicates = 40	2 seasons*5 cm *2 replicates = 20
# of samples for dead foraminiferal analysis	4 seasons*2 cm *2 replicates = 16	4 seasons*2 cm *2 replicates = 16	2 seasons*2 cm *2 replicates = 8

Table 2.2: Summary of work protocol modification			
	Hyams-Kaphzan et al. (2009)	Schönfeld et al. (2012)	Current study
Sampling devices	Box corer Tube (Ø=5.4 cm)	Box corer Tube (Ø=8 cm)*	Box corer Tube (Ø=5.3 cm)
Core penetration depth (cm)	10 cm	Top cm	5 cm (live) 2 cm (dead)
Preservative	Rose Bengal solution (2g/liter) Ethanol 95%	Rose Bengal solution (2g/liter) Ethanol >70%*	Rose Bengal solution (2g/liter) Ethanol 95%
Sieve size	63µm	63µm	63µm
Splitting technique	Counted entirely	Wet or dry splitters	Counted entirely (live), dry splitter (dead)
Faunal analysis	Living fauna	Living fauna	Living and dead fauna
Picking	Wet	Wet or dry	Dry
# of replicates	No replication	Triplicate	Duplicate**
Population density	10 cm^3	50 cm^3	10 cm^3

* Advisory recommendation.

**The third replicate was analyzed when inconsistency between replicate emerged or the number of specimens was insufficient (<20 specimens/sample).

3. RESULTS

3.1. Environmental conditions

3.1.1. Water column

Temperature and salinity varied seasonally at the surface as well as at the bottom of the water column in all sampling stations (Figure 3.1.1). The warmest temperatures were recorded in July 2012 (~30 °C), and the coldest in January 2012 (~18 °C). During winter the water column was mixed, with similar temperatures at the surface and at the bottom. A distinct thermocline at ~15 m water depth developed during spring, when sea surface temperature (SST) was 5 °C warmer than the bottom water temperature (Figure 3.1.1). In July the thermocline weakened in an order of 1°C, and in fall a well-mixed water column appeared (Figure 3.1.1). The fall sampling episode (November) took place a few days after a storm event that contributed to the mixing of the water column. The lowest salinity surface values of 39 psu were recorded in January and May 2012 (Figure 3.1.1). Highest values of 39.6 psu were recorded in November. During spring the salinity was lower by 0.15 psu at station PL3 comparing with PL29 and PL64. In winter and fall the surface salinity values were similar to bottom water values. Higher values prevailed in the top and bottom water column with sharp decrease between 15-20m depth, during summer (July). In spring (May) a decrease of ~0.2 psu was recorded at the top 20 m (Figure 3.1.1).

O_2 concentration in the bottom water was similar in all three stations, except in the spring (May) where PL3 O_2 concentration was lower by 1.12 mg/L than at stations PL29 and PL64 (Figure 3.1.2). In general the lowest concentration occurred during summer (5.98 mg/L) at all three stations, while the highest concentration occurred during spring (7.66 mg/L) at stations PL29 and PL64 and winter (7.21 mg/L) at PL3 (Figure 3.1.2).

Chl a concentration in the bottom water show similar seasonal variation in all three stations (<0.1 µg/L) except for spring were PL64 concentration was higher by >1.5 µg/L then PL29 and PL3 (Figure 3.1.3). Lowest Chl a concentration (~0.35 µg/L) occurred during winter and fall, while highest concentration (~0.7 µg/L) occurred in PL3 and PL29 during summer (July). Although PL64 was not sampled during summer, and the late spring value (June) was used. (Figure 3.1.3).

A wide dark sludge spot was observed at the water surface of station PL3 in all samplings except for the spring sampling. During fall the sludge spot was visible a few hundred meters east of station PL3.

3.1.2. Sediment properties

Sediment cores of stations PL3 and PL29 are shown in Figure 3.1.4.

The sediment of station PL3 was fluffy, dark colored and muddy, and was clearly heavily contaminated by fetid sewage sludge. At station PL29 the sediment was bright or dark brown silt, appearing darker than described by Hyams-Kaphzan et al. (2009). Station PL64 consists of a bright brown sand with no residues of the sludge.

Mode grain size was higher at PL29 and PL64 than at PL3 except for winter (January) where the difference (~0.1 µm) is not significant (Figure 3.1.5 a-c). At PL3 the highest mode was recorded during winter (>119 µm) in all 5 cm, while the lowest recorded during fall (<60 µm). During spring the grain size mode drops sharply with sediment depth from 108 µm at the top 0-1cm to as low as 12 µm at 4 cm of this season (Figure 3.1.5a). At both PL29 and PL64 the grain size distribution is similar (~131 µm) throughout 0-5 cm and no seasonal differences were observed (Figure 3.1.5b-c). At PL29 and PL64 the organic matter removal had no effect on grain size distribution, while at PL3 a small shift towards finer grain size was observed (Figure 3.1.6).

TOC content was higher by an order of magnitude at PL3 as compared to PL29 and PL64 (Figure 3.1.5d-f). At PL3, the highest TOC content was detected during summer and fall in the upper 2 cm of sediment (>3 wt.%) dropping at the third cm to lowest content (<1 wt.%) similar to spring average concentration of 0.9 wt.% At PL29 and PL64 low TOC concentration of 0.4 wt.% on average prevailed during all seasons of 2012, with some fluctuation recorded at PL29 (Figure 3.1.5).

Chl a concentration in the top sediment layer was ~0.7 µg/g higher at PL3 than at PL29, except for summer (July). The highest concentrations of 3.25 and 2.6 µg/L occurred at PL3 and PL29 respectively during May and July (only at PL3). The lowest concentrations of 1.6 and 0.7 µg/L occurred at PL3 and PL29 respectively during January and July (only for PL29) (Figure 3.1.7).

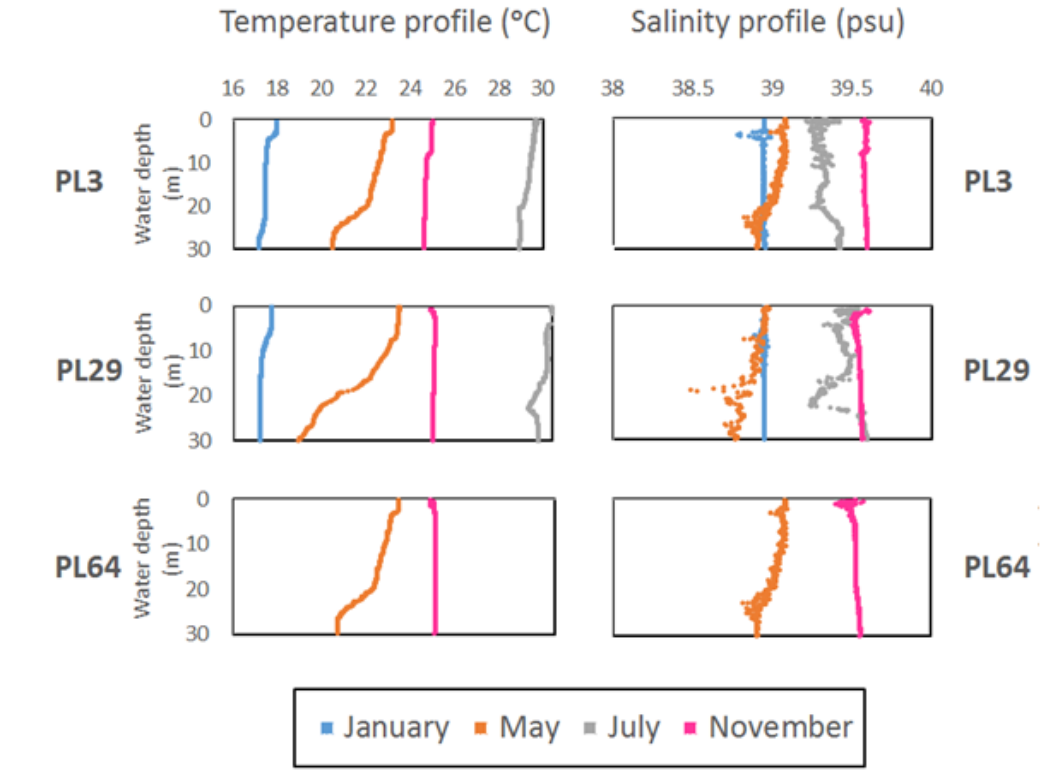


Figure 3.1.1: CTD – Temperature (°C) and salinity profiles (psu) at stations PL3, PL29 and PL64, from January to November 2012

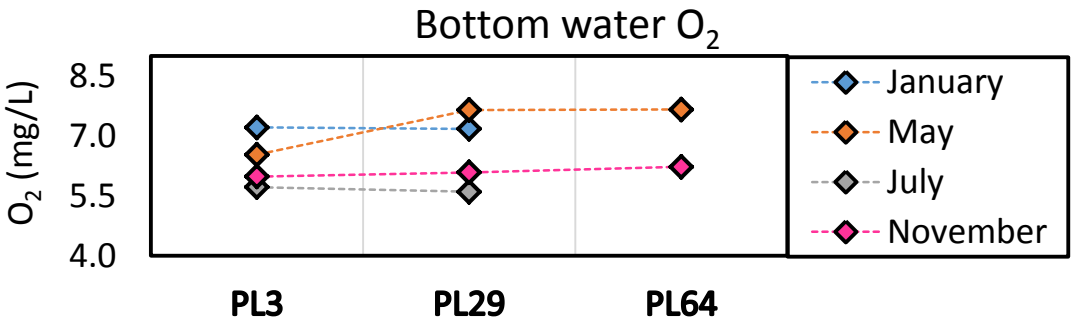


Figure 3.1.2: Dissolved oxygen concentration (mg/L) in bottom water of the sampling stations from January to November 2012.

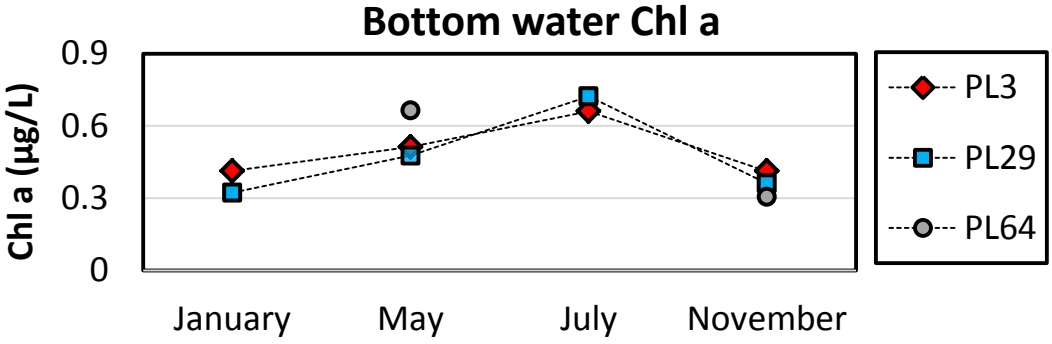


Figure 3.1.3: Chl a concentration (µg/L) in the bottom water of the sampling stations from January to November 2012.

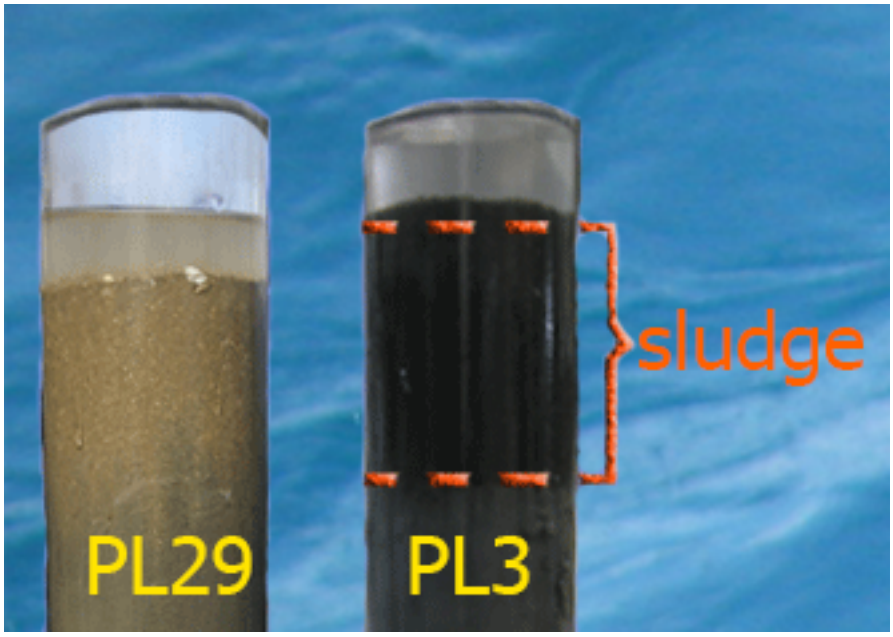


Figure 3.1.4: Sediment cores taken from sampling stations.

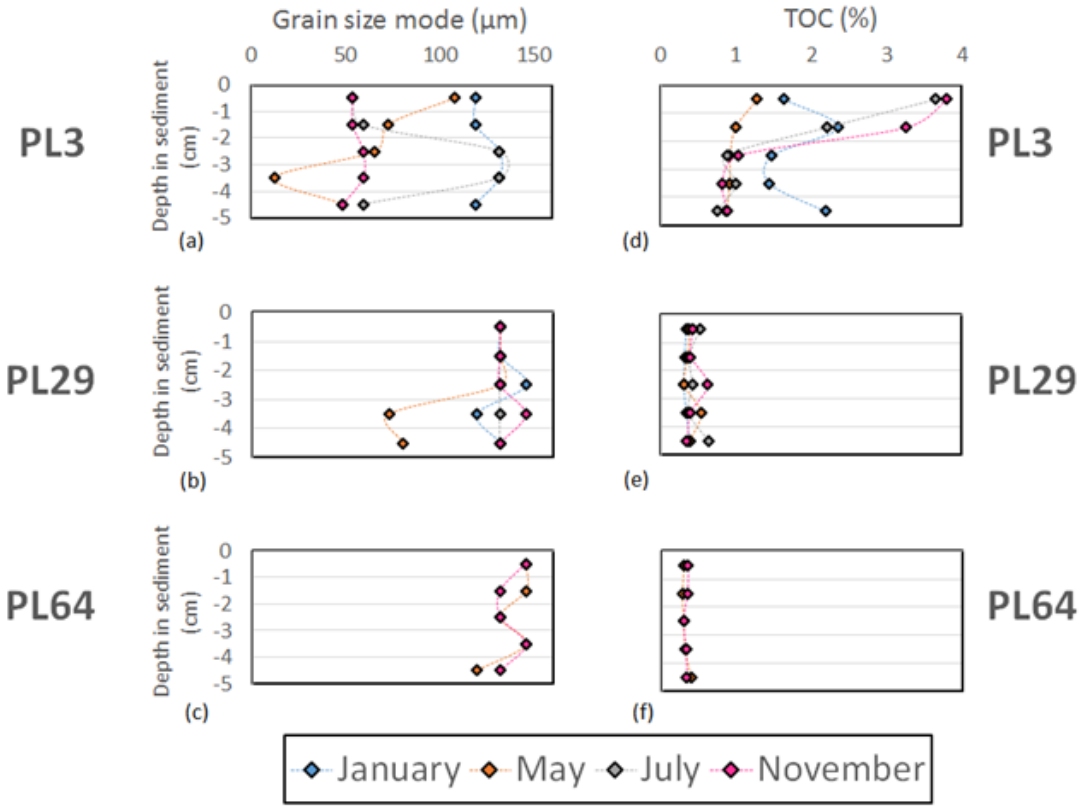


Figure 3.1.5: Grain size mode (µm) and total organic carbon (TOC wt.%) profiles at PL3 (a,d), PL29 (b,e) and PL64 (c,f), from January to November 2012.

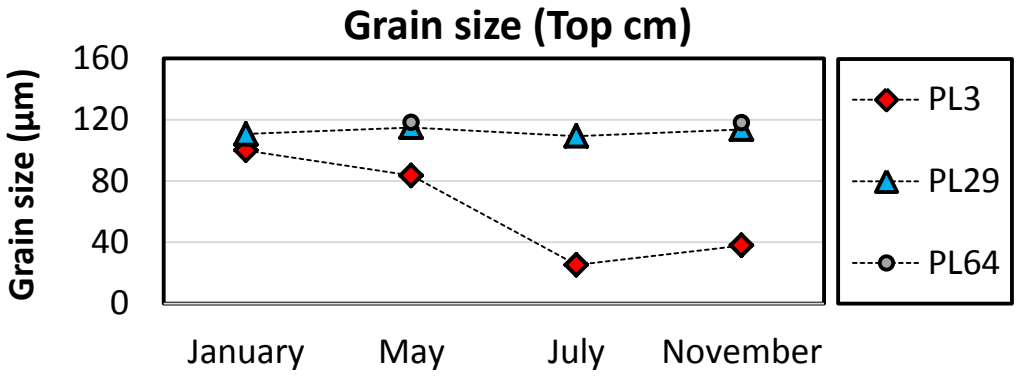


Figure 3.1.6: Top cm grain size mode (µm), after organic matter removal of the sampling stations from January to November 2012.

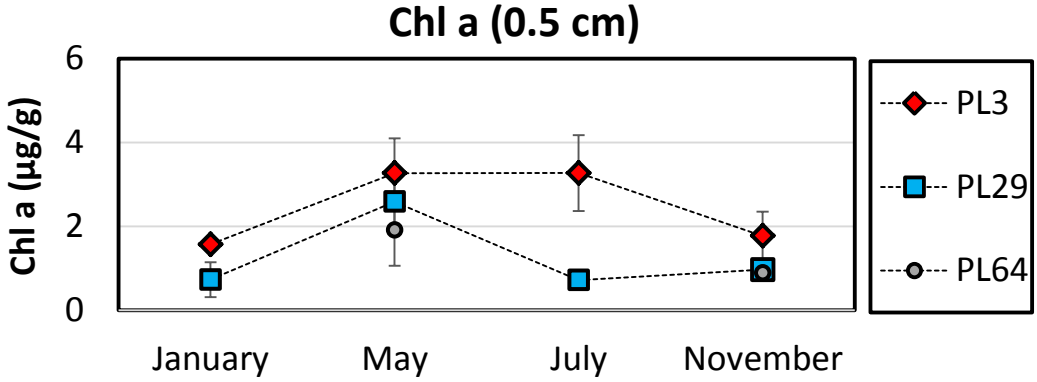


Figure 3.1.7: Chl a concentration (µg/g) in the top sediment (0.5 cm) of the sampling stations from January to November 2012.

3.2. **Living (stained) benthic Foraminifera:**

A total of 149 species were identified in the living assemblage, of them, only 52 species were recorded in all three stations. Most of the dominant species (>5% in at least one sample; species of <4 specimens were not included) were found in all three station with differences in their relative abundance.

3.2.1. Numerical abundance and diversity pattern (Table 3.2.1)

The maximal total standing stocks (TSS) per sediment volume, 10cc at PL3 was ~20 foraminifera/10cc (summed over the top 5 cm) with average TSS of 6.4±6.3 (std. error of the mean); the maximal TSS at PL29 and PL64 is ~109 specimens/10cc and the average TSS is 68±21 and 30±11 respectively. In most cases higher TSS was recorded in the upper 1 cm of sediment layer.

Species richness at PL3 is half or less that of PL29 and PL64. The maximal species at PL3 is 36 species with an average of 16±10 (std. error of the mean), the maximal species richness at PL29 and PL64 is 77 species and the average species richness is 64±9 and 52±12 respectively.

Pielou's Evenness index was calculated for a better estimation of community structure as it is not dependent on population size. Low variation between stations was observed, with the highest value (0.92±0.05) recorded at PL3, and the lowest (0.72±0.04) at PL29.

3.2.2. Abundance versus species richness seasonal variation

Seasonal fluctuation of live foraminiferal abundance and species richness summed over the top 5 cm is shown especially at PL3 (Figure 3.2.1a-c) where highest numerical abundance (19±3 specimens/10cc) and species richness (35 species) recorded during winter and the lowest (4±2.5 specimens/10cc) during the rest of the year (spring, summer and fall; Figure 3.2.1a). At PL29 the seasonal fluctuations were very low with maximal numerical abundance of 82±38 specimens/10cc and species richness (68 species) during summer and minimum values during spring (54±17 specimens/10cc and 61 species; Figure 3.2.1b). At PL64 values of 26±14 and 34±12 specimens/10cc of 49 and 55 species were recorded during spring and fall respectively (Figure 3.2.1c).

3.2.3. The distribution pattern of foraminiferal groups

The division into three groups according to their test composition summed over 0-5 cm and averaged between seasons is shown in Figure 3.2.2.

At PL3 the variation between samples was very high, the most abundant groups belonging to the agglutinated foraminifera mainly with organic cement or to the perforate calcareous foraminifera (~45%; Figure 3.2.2a). At PL29 and PL64 the assemblages were characterized by high dominance (~65%) of perforate calcareous foraminiferal tests and moderate values (<30%) of organically-cemented agglutinants (Figure 3.2.2b-c). All three stations reveal very low (≤10%) relative abundance of porcelaneous shells (miliolids; high magnesium calcite) (Figure 3.2.2a-c).

3.2.4. Benthic foraminiferal living assemblages

A total of 520 live (stained) specimens of >60 different species were collected from the top 5 cm of sediment during January, May, July and November 2012 at PL3 (Table 3.2.1). The highest number of stained specimens (5601) and species richness (>130 species) were collected at PL29 (Table 3.2.1). At PL64 moderate numbers (1286 stained specimens of 90 species; Table 3.2.1) were collected but it was sampled only during spring and fall, compared to 2583 and 198 specimens collected in the same period at PL29 and PL3 respectively. The most abundant taxa are shown in Table 3.2.2, Plate 1.

Among the calcareous foraminiferal species, *Ammonia tepida* and *Bolivina striatula* occurred in relatively high numbers at PL29 and PL64, *A. tepida* was the most common species in those sites with 20 and 8 specimens per 10cc on average in the top cm and less abundant at PL3 (<10%; Table 3.2.2). Other calcareous taxa such as *Fursenkoina acuta* occurred in high numbers in only one sampling season at PL29 and PL64, while completely absent from station PL3 (Table 3.2.2).

Miliolids were rare in all sampling stations. The most abundant species of this group was *Quinqueloculina bosciana* that was found in relatively high numbers (up to 7.1 specimens per 10cc) at station PL29 and PL64 representing >5% of the assemblage at PL29 (Table 3.2.2) while lower numbers were found at PL3.

The organically-cemented agglutinants had the highest relative abundance at PL3 of >40% compared to PL29 and PL64 with ~25% of the assemblage at all samples. At all three station *Eggerelloides scaber* was the most dominant species of the organically-cemented agglutinants followed by *Acostata mariae* (Table 3.2.2).

In general although the three stations shared the same pool of species, some differences were observed:

(1) Species that were found only in one sampling station: *Cribroelphidium poeyanum* and *Elphidium crispum* (PL3), *Astrononion stelligerum*, *Cassidulina carinata, Triloculina marioni* and *Trochammina* sp. (PL29) and *Buccella granulata* (PL64).

(2) Species that were missing at one station: *Ammonia beccarii, Asterigerinata mamilla, F. acuta, Globulina gibba, Rosalina bradyi, Lagenammina atlantica, Textularia truncata* (PL3), *Buliminella elegantissima*, *Elphidium fabum*, *Fissurina lucida* and *Lagena substriata* (PL64).

3.2.5. Seasonality of foraminiferal groups and selected species

The seasonal variations in numerical abundance of the five most common species at stations PL3, PL29 and PL64 summed over 0-5 cm is shown in Figure 3.2.3. At station PL3 all dominant species had higher numerical abundance during winter; *A. tepida*, *B. striatula*, *Q. bosciana*, *A. mariae*, and *E. scaber* (1-2 specimens/10cc; Figure 3.2.3). Specimens of those species were barely found during fall, except for 7 specimens of *E. scaber*. A few rare species were found only during one season; winter (*Hopkinsina pacifica*), spring (*Leptohalysis scotti*) and summer (*Bulimina* sp. and *Sahulia conica*). No miliolids were found during November and only three specimens found during July.

At station PL29 the most dominant species were the perforate calcareous *A. tepida* and *B. striatula* with up to 32 and 13 specimens per 10cc respectively, and agglutinant *E. scaber* (with up to 10 specimens/10cc). For most of the dominant species higher numerical abundance as well as high variation between replicates was found during summer or fall, e.g. *A. tepida* (summer; 26±10 specimens/10cc), *B. striatula* (summer; 9±6 specimens/10cc), *Q. bosciana* (fall; 6±2 specimens/10cc) and *E. scaber* (summer and fall; 7±1 and 8±3 specimens/10cc respectively)(Figure 3.2.3).

At station PL64 the two most dominant species *A. tepida* and *E. scaber* showed higher numerical abundance during fall than spring. Other species such as *B. striatula* and *A. mari*ae showed low differences between sampling seasons (Figure 3.2.3).

3.2.6. Vertical distribution and Average Living Depth (ALD; Figure 3.2.4)

In general PL3 had lower average living depth (ALD) than stations PL29 and PL64. Living foraminiferal specimens were found at PL29 and PL64 down to 5 cm in the sediment in all sampling seasons (and replicates), although the numerical abundance decreased drastically with depth during summer and fall, while during winter a clear subsurface maxima was observed (Figure 3.2.4). At PL3 most of the year live specimens were found down to 3-4 cm, with lowest penetration depth during fall (2 cm) and highest during spring (down to 5 cm at one of the replicates), the numerical abundance was higher in the upper 2 cm of sediment than below (Figure 3.2.4). Highest ALD was detected during spring at PL3 (1.7±1.2), PL29 (2.6±0.4) and PL64 (2.3±0.5) while lowest ALD was detected during fall at all three stations 0.7-2.2 cm (Figure 3.2.4).

3.2.7. In-sediment distribution pattern of selected species

Ammonia tepida, the most common species at PL29 (>10 specimens/10cc) and at PL64 (up to 14 specimens/10cc) maintained high numerical abundance throughout the top 5 cm (Figures 3.2.5, 3.2.6). At PL3 higher numerical abundances were found in the upper 2 cm of sediment, up to 4 specimens/10cc (Figure 3.2.7).

Eggerelloides scaber was found in relatively high numbers in all depths at PL29 (up to 21 specimens /10cc) and at PL64 (up to 7 specimens /10cc) with some fluctuations in its vertical distribution (Figures 3.2.5, 3.2.6). At PL3 higher numerical abundances were found at the upper cm, decreasing sharply with depth during January 2012, and remaining somewhat even (~ 0.6) during the rest of the year (Figure 3.2.7).

Bolivina striatula, *Q. bosciana* and *A. mariea* - were all found mainly in the upper 2 cm at PL29, decreasing sharply downwards. A similar pattern was detected at PL3 during winter. During the rest of the year lower number of specimens were found in all sediment depths. At PL29 during summer *A. mariea* had higher numbers (>7 specimens/10cc) down to the 3rd cm of sediment.

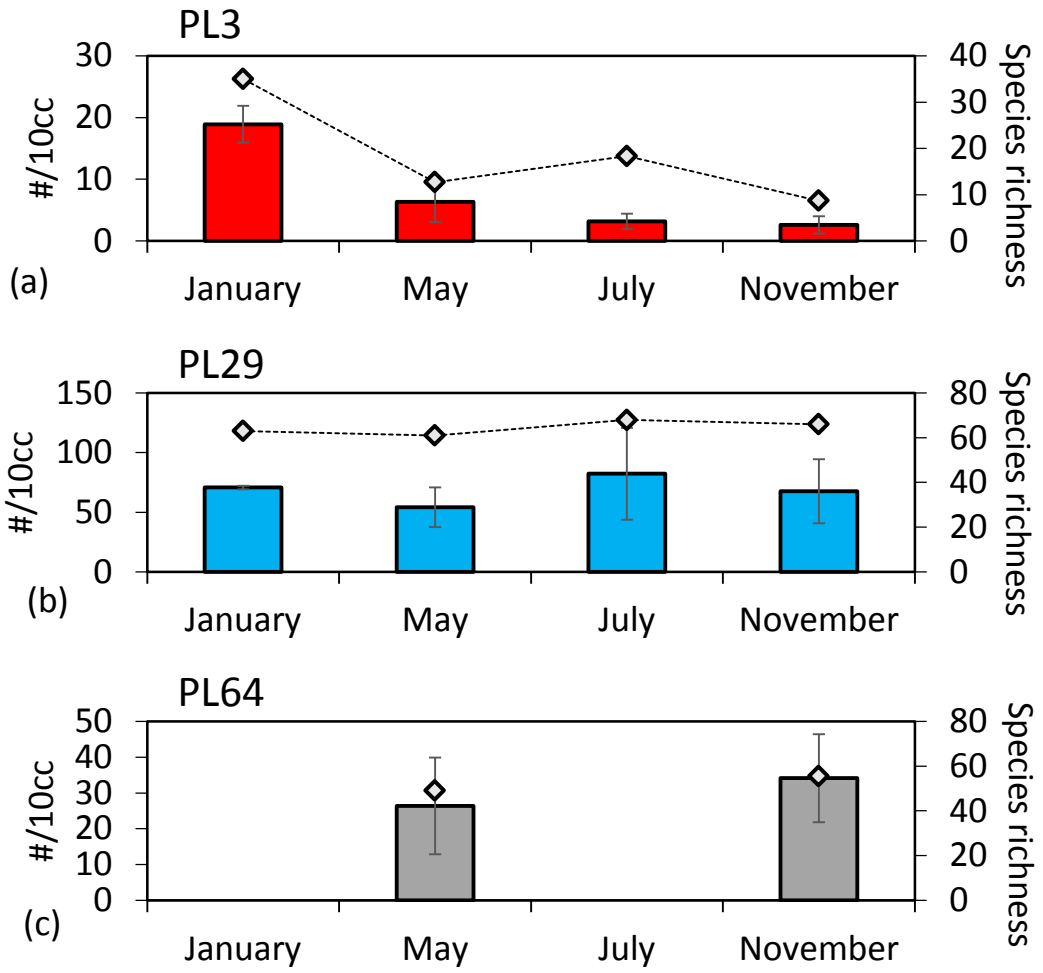


Figure 3.2.1: TSS (bars; number of specimens per 10cc) and species richness (diamonds; number of species) summed over the top 5 cm at (a) PL3, (b) PL29 and (c) PL64. January to November 2012. Note PL64 was sampled only twice (May and November) and change of scale.

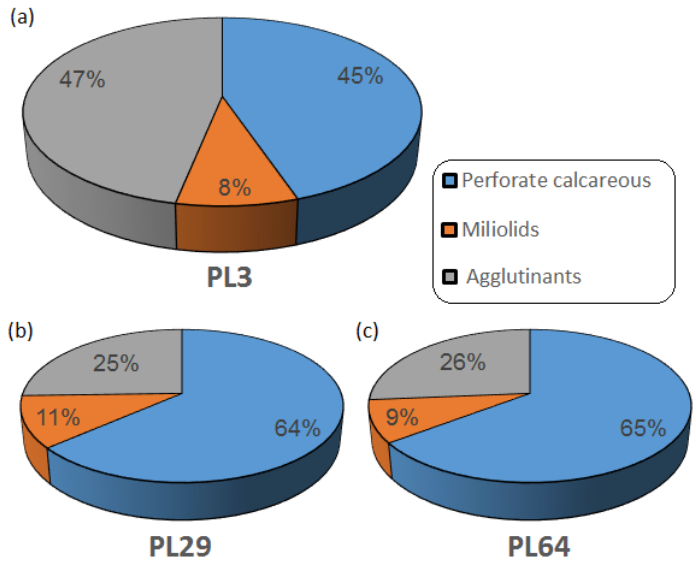


Figure 3.2.2: Relative abundance of the major foraminiferal groups summed over 0-5 cm, then averaged between seasons at (a) PL3, (b) PL29 and (c) PL64.

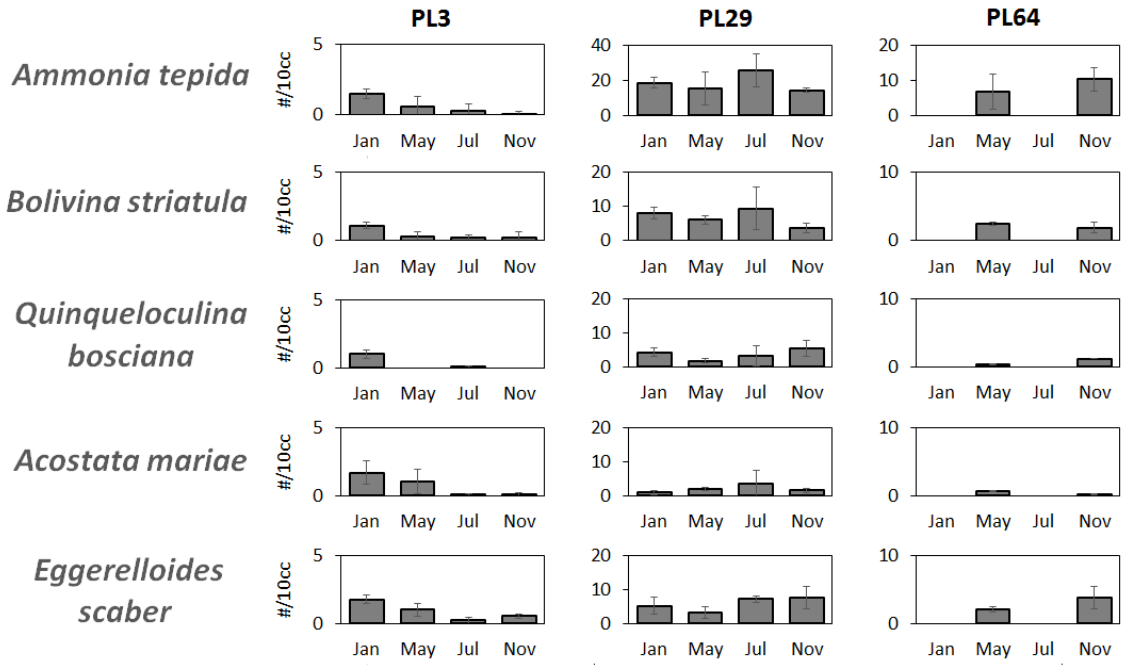


Figure 3.2.3: Seasonal variation in numerical abundance of the five most common species summed over 0-5 cm at PL3, PL29 and PL64. Note change of scale, and that PL64 was sampled only twice (May and November).

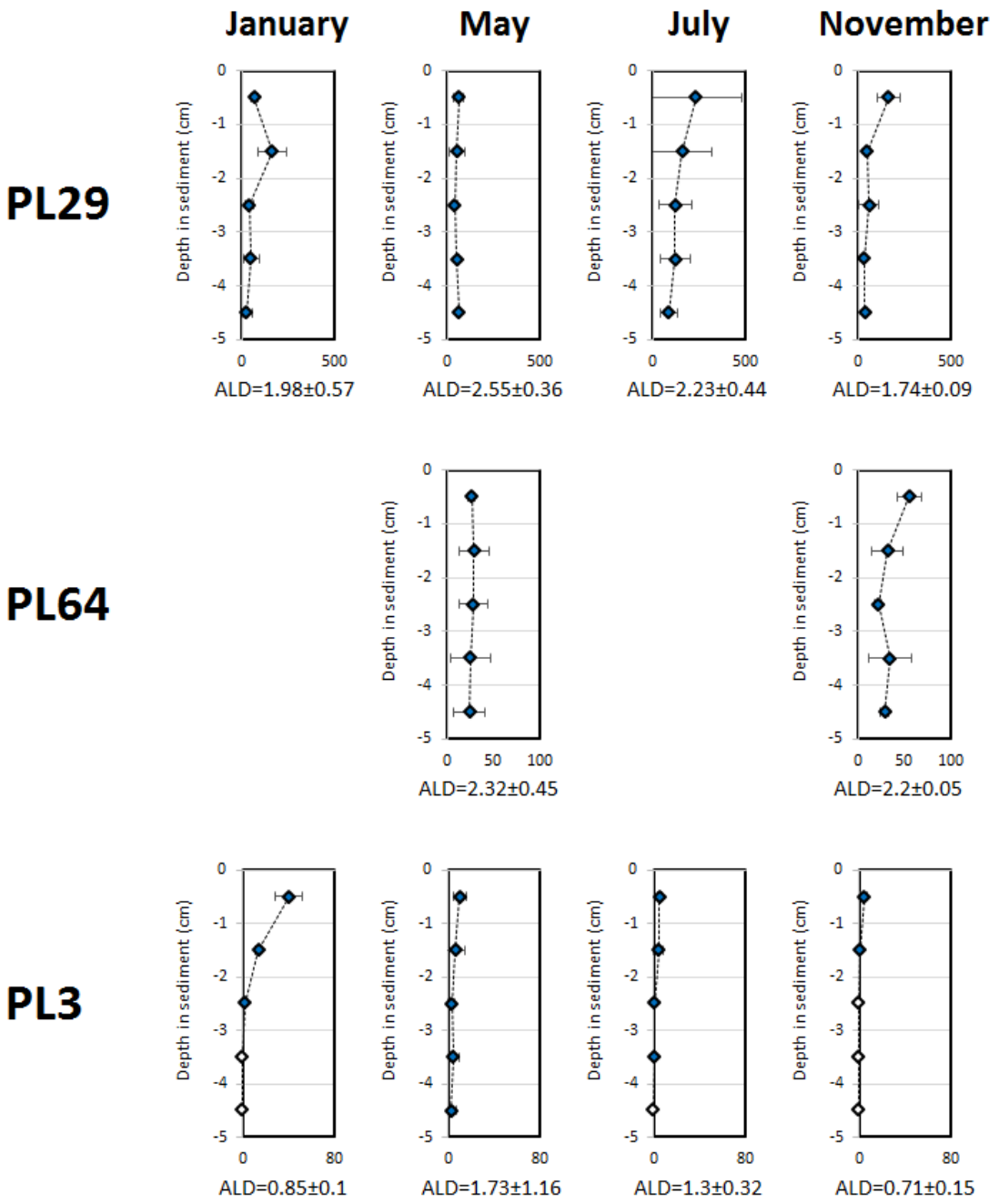


Figure 3.2.4: In-sediment distribution per 10cc and average living depth at PL3, PL29 and PL64. Note change of scale and PL64 was sampled only twice (May and November).

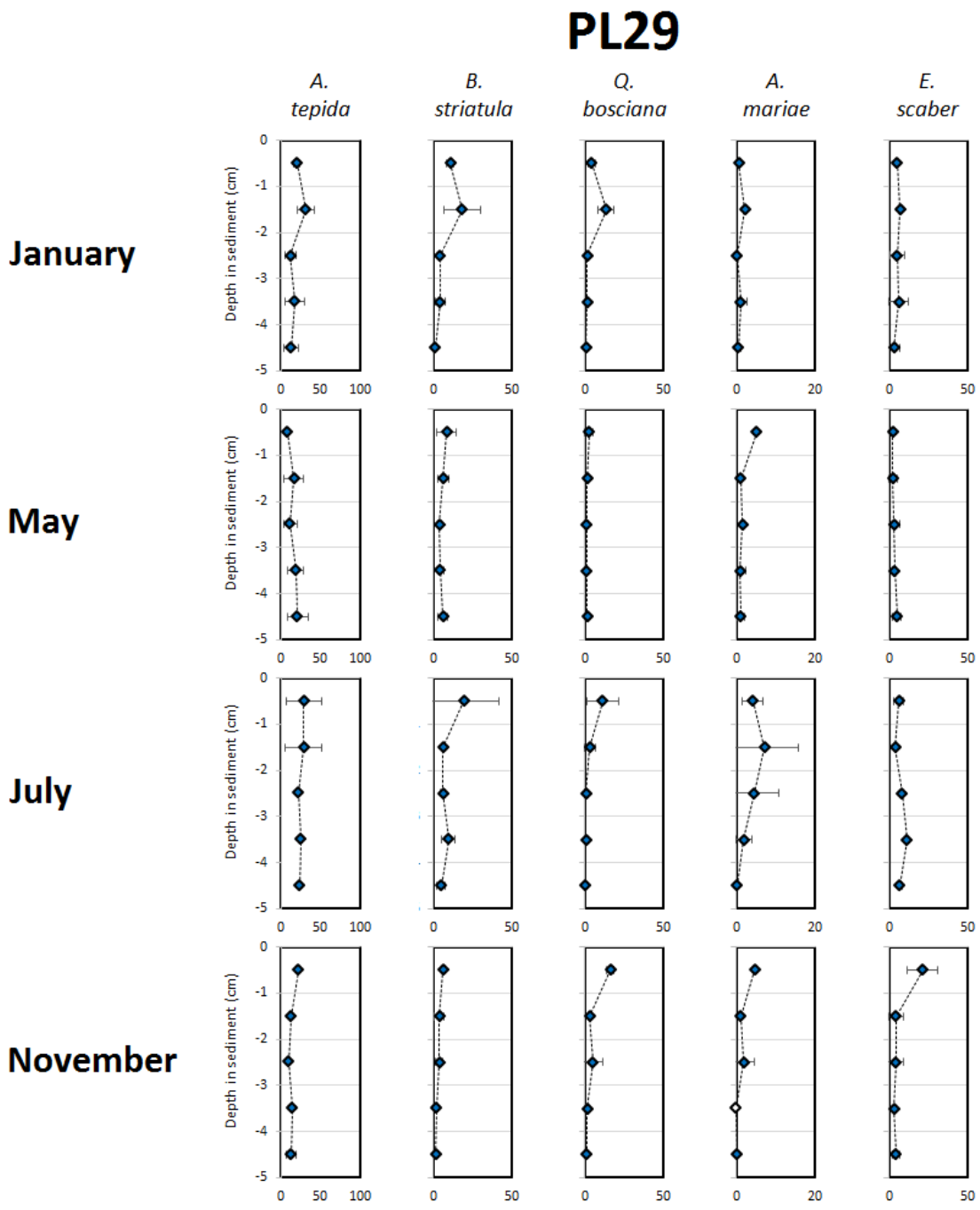


Figure 3.2.5: In-sediment distribution per 10cc of the most common foraminiferal species at station PL29. Note change of scale between species.

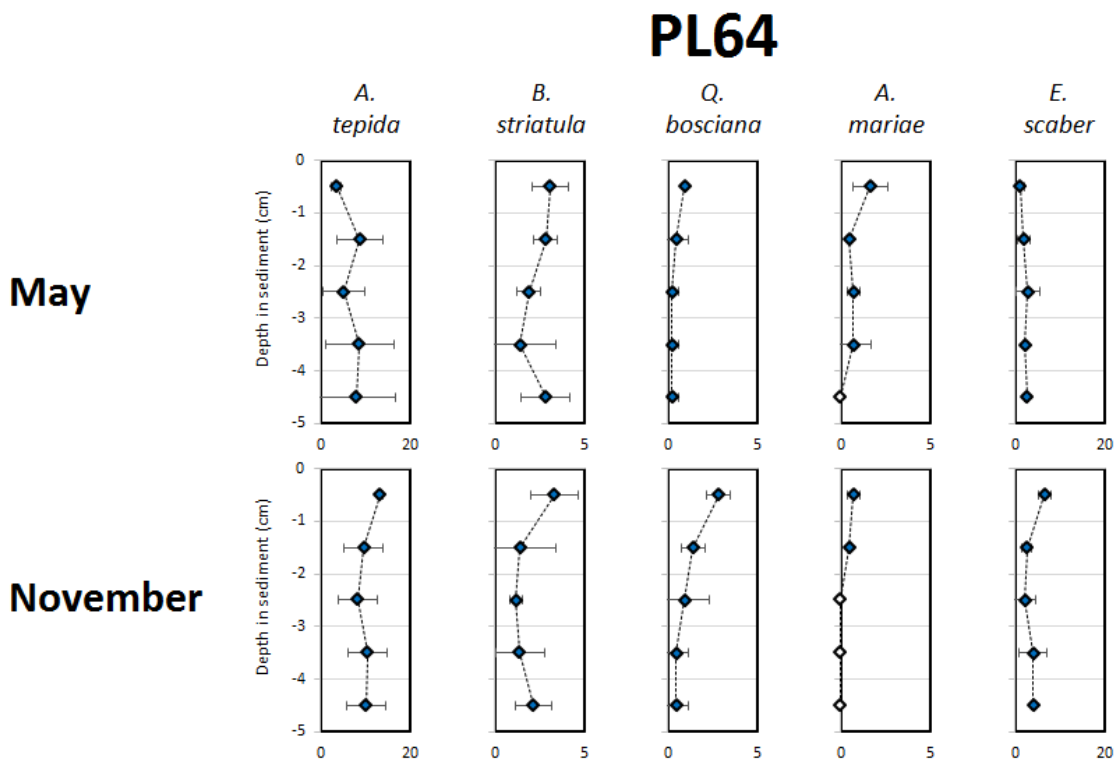


Figure 3.2.6: In-sediment distribution per 10cc of the most common foraminiferal species at station PL64. Note PL64 was sampled only twice (May and November) and change of scale between species.

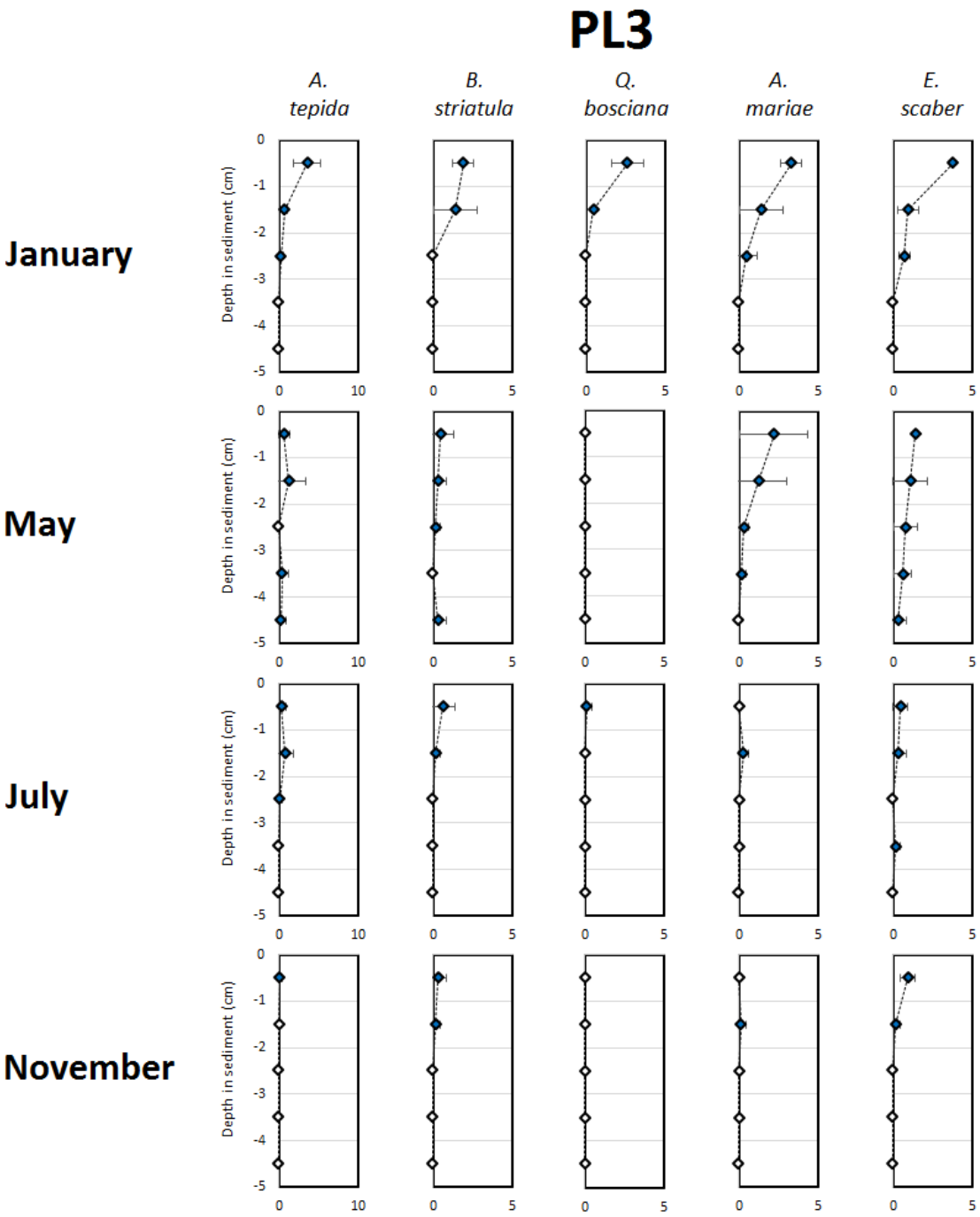


Figure 3.2.7: In-sediment distribution per 10cc of the most common foraminiferal species at station PL3. Note change of scale.

Table 3.2.1: Diversity indexes of living foraminiferal community and annual numerical abundance of selected species per 10cc (summed over 0-5 cm) of the three sampling stations			
	PL3	**PL29**	**PL64**
Collected specimens	520	5601	1286
Total species richness	60	130	90
Margalef index	12.15	15.87	13.55
#/10cc	6.4±6.3	68±21	30±11
Average species richness	16±11	65±9	52±12
Average Pielou's Evenness	0.92±0.05	0.72±0.04	0.77±0.04
Ammonia tepida	0.54±0.6	18±7	8.6±4
Bolivina striatula	0.38±0.43	6.7±3.4	2.1±0.6
Quinqueloculina bosciana	0.26±0.46	3.8±0.5	0.8±0.5
Acostata mariae	0.59±0.83	2±1.9	0.5±0.3
Eggerelloides scaber	0.76±0.65	5.9±2.5	3±1.4

Table 3.2.2: Living assemblage four most common foraminiferal taxa (in decreasing order of their relative abundance) found at the three sampling stations summed over 0-5 cm and averaged between seasons.		
PL3 (Jan-Nov. 2012)	PL29 (Jan-Nov. 2012)	PL64 (May & Nov. 2012)
Eggerelloides scaber (14.1±10.5%)	*Ammonia tepida* (27±6.5%)	*Ammonia tepida* (27.4±5.3%)
Acostata mariae (7.1±8.6%)	*Bolivina striatula* (9.6±3%)	*Eggerelloides scaber* (10±2.2%)
Ammonia tepida (7.1±6.5%)	*Eggerelloides scaber* (8.6±2.9%)	*Bolivina striatula* (7.8±3.8%)
Bolivina striatula (6.3±8.3%)	*Quinqueloculina bosciana* (5.3±2.4%)	*Ammonia parkinsoniana* (3.6±2%)

3.3. Dead benthic foraminifera

A total of 11,600 dead specimens of >140 species were collected during this study. The majority of the species were found in all three stations.

3.3.1. Numerical abundance and diversity pattern

The maximal numerical abundance per 10cc at PL3 was ~14,900 with an average of 9411±3681 (std. error of the mean); the maximal numerical abundance at PL29 and PL64 is ~24,000 foraminifera/10cc with an average of 20,888±2325 and 15,321±2015 respectively (Table 3.3.1). The maximal species richness at PL3 is 84 species with an average of 79±4, while the maximal value at PL29 and PL64 is 85 species and the average species richness is 80±8 and 84±2 respectively (Table 3.3.1).

3.3.2. Seasonal variation in dead foraminiferal abundance versus species richness at the top 2 cm

Seasonal fluctuation in foraminiferal abundance per 10cc and species richness of foraminiferal tests at the top 0-2 cm is shown in Figure 3.3.1a-c. At both stations PL3 and PL29 highest numerical abundances recorded during summer (~15,000 specimens/10cc and ~24,000 specimens/10cc respectively), while lower values (5500-9500 specimens/10cc and 18,000-21,000 specimens/10cc respectively) were found during the rest of the year (Figure 3.3.1a-b). Species richness varied between 54-69 species in all three stations. At PL3 the seasonal differences were masked by high variation between replicates while at PL29 lowest values (56 specimens) were found during summer (Figure 3.3.1a-b). At PL64 values of 13,896±559 and 16,746±611 specimens/10cc were recorded with 65 species during both seasons (Figure 3.3.1c).

The distribution of specimens between the top two cm is shown in Figure 3.3.2. At PL3 relatively low numerical abundance was found at both depth (0-1 and 1-2 cm) during winter and spring (~7,000 specimens/10cc), while during summer and fall higher numbers were found (especially at the deeper cm; 19,568 ±1648 and 18,538 ±3203 respectively), and the maximal variation between replicates was found during summer at the top cm (11,949 ±5349 specimens/10cc; Figure 3.3.2). At PL29 the numerical abundance was similar between seasons as well as between depth (~20,000 specimens/10cc) except for summer high numerical abundance and high standard deviation at the top cm (28,569 ±8694 specimens/10cc; Figure 3.3.2). Station PL64 had much lower variation between

samples in both distribution with depth as well as in relatively low standard deviation between replicates (~7,000 specimens/10cc), spring top cm had a bit higher numbers (14,074 ±3196 specimens/10cc; Figure 3.3.2).

3.3.3. Distribution pattern of foraminiferal groups

In all three sites the perforate calcareous benthic foraminifera were the most common group (>70%), while miliolids, the second most common group, accounted for 10-20% of the assemblage (Table 3.3.1). Both organically-cemented and carbonate-cemented agglutinants foraminifera were rare (<5% each; Table 3.3.1).

At PL29 and PL64 the variation between seasons as well as within replicates were very low (<3%), while at PL3 the variation of the perforate calcareous group between seasons was slightly higher even within replicates (up to 7%), during winter and spring (~4%).

3.3.4. Benthic foraminiferal dead assemblages

A total of 4907 dead foraminiferal tests were collected during January, May, July and November 2012 at PL29. At PL3, 4531 dead specimens were found between January to November. At PL64 2199 specimens were collected during spring and fall. At each station >100 species were found (Table 3.3.1). The most abundant taxa are shown in Table 3.3.2, Plate 2.

Among the calcareous taxa, *A. tepida*, *Ammonia parkinsoniana* and *Porosononion subgranosus,* the three most common species in the dead assemblage, occurred in high numbers at all three stations (Figure 3.3.3 a-f, Table 3.3.1, 3.3.2). *Ammonia tepida*, the most common species (>24%) in all three stations (Table 3.3.2), with extremely high numerical abundance at PL29 (especially during summer; 7634 ±1648 specimens/10cc), comparing to lower values of 2100-3800 per 10cc at PL3 and 2900-4500 specimens/10cc at PL64 (Figure 3.3.3 a). *Ammonia parkinsoniana* the second most dominant species had higher relative abundance at PL29 (18±4%) and PL64 (23±1%) comparing with station PL3 (11±1%), in all three stations the seasonal variation was very low (Table 3.3.2, Figure 3.3.3b). *Porosononion subgranosu*s had similar relative abundance at all three sampling stations (9-10%; Table 3.3.2), furthermore at PL29 no seasonal variation in numerical abundance was found (1700-2100 specimens/10cc) and was very low at PL64 (1200±4 and 1450±36 specimens/10cc during spring and fall respectively). While at PL3 *P.*

subgranosus numerical abundance was twice as high during summer (1560±522 specimens/10cc) comparing to the rest of the year (600-900 specimens/10cc; Figure 3.3.3c). However other calcareous taxa such as *A. beccarii* and *Ammonia inflata* had higher relative abundance at station PL3 (9±2.7% and 4±1% respectively) comparing with the remote stations PL29 and PL64 (*A. beccarii* - 4-5% and *A. inflata* - 2-3%; Table 3.3.2). At PL3 *A. beccarii* had high fluctuations between seasons and replicates, as oppose to PL29 and PL64 lower seasonal variation (Figure 3.3.3d,e).

The miliolids are the second most common group in the dead assemblage, among them the most dominant genus is *Adelosina* representing 9% of the assemblage at stations PL29 and PL64 comparing to 6±1.7% at PL3 (Table 3.3.2). Much like to the rest of the dominant species (described above), the numerical abundance of this genus was highest during summer (1116±455 specimens/10cc) comparing to the rest of the year (<550 specimens/10cc) at PL3 while relatively low seasonality was found at PL29 and PL64 (Figure 3.3.3f). Furthermore, at station PL29 >15% of all *Adelosina* specimens showed extensive bio-erosion markings (borings), and most of them were extremely eroded in the outer layer of their tests (Plate 3). This was less common at station PL3 and PL64 (3% and 8%), but most of the smaller tests had thin translucent walls and were partially or completely filled with pyrite.

The carbonate-cemented agglutinant species *T. agglutinans* was the most common of this group, although it represented <3.5% in all samples that were examined. The organically-cemented agglutinated foraminifera were preserved poorly in the dead assemblage, therefore no dominant species is shown.

3.3.5. Test abnormality

Deformed foraminiferal tests were found in all stations, most of them belonging to *A. tepida* and *A. parkinsoniana* or to the genus *Bolivina* (Table 3.3.3). The portion of deformed test of this taxa decreased with distance from the outfall from 20-30% at station PL3 to 7-15% at PL64 (Table 3.3.3). Abnormality was less common in other species such as *A. beccarii, A. inflata, P. subgranosus, Textularia earlandi, T. agglutinans* and some *Cribroelphidium* species, and the percentage of deformed tests were constant at all stations. Deformation of tests include abnormal chamber shape or size, supernumerary chambers or twisted chambers arrangement, as well as twisted coiling that was found in biserial forms.

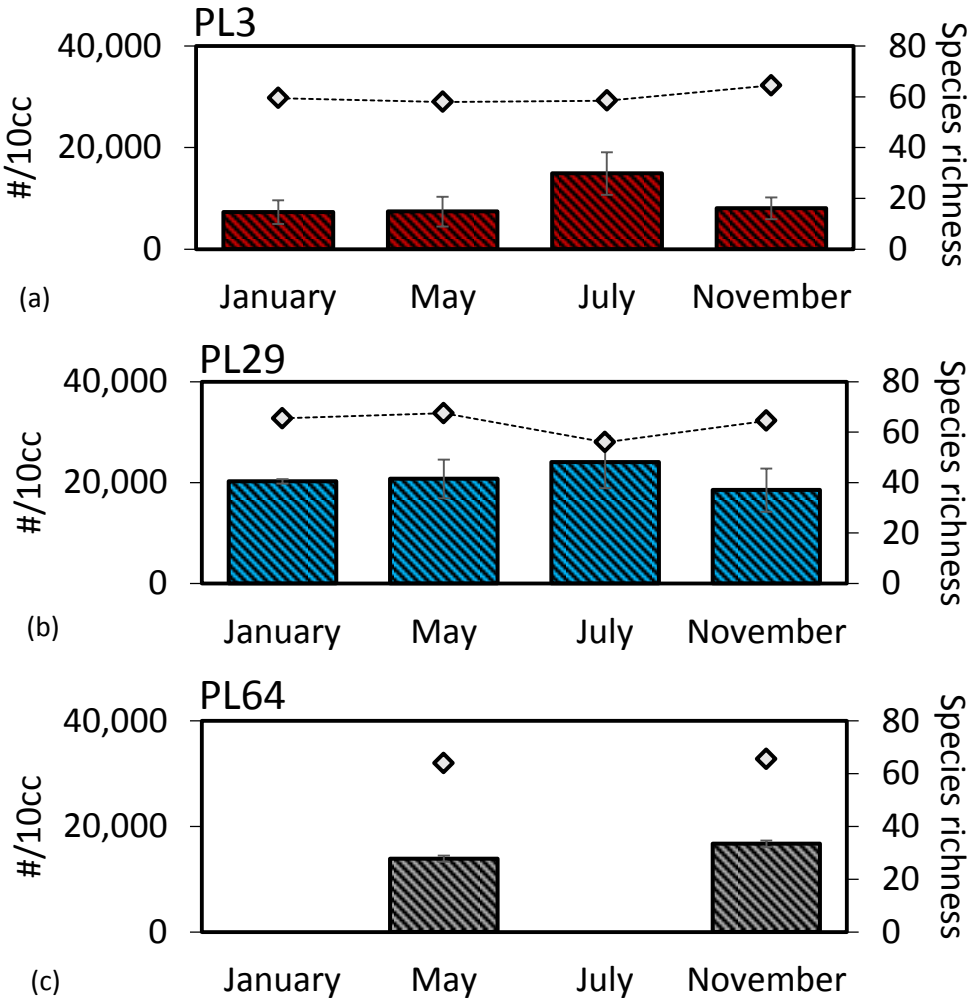


Figure 3.3.1: Numerical abundance (bars; number of specimens per 10cc) and species richness (diamonds; number of dead foraminiferal species) summed over the top 2 cm at (a) PL3, (b) PL29 and (c) PL64. January to November 2012. Note PL64 was sampled only twice a year (May and November).

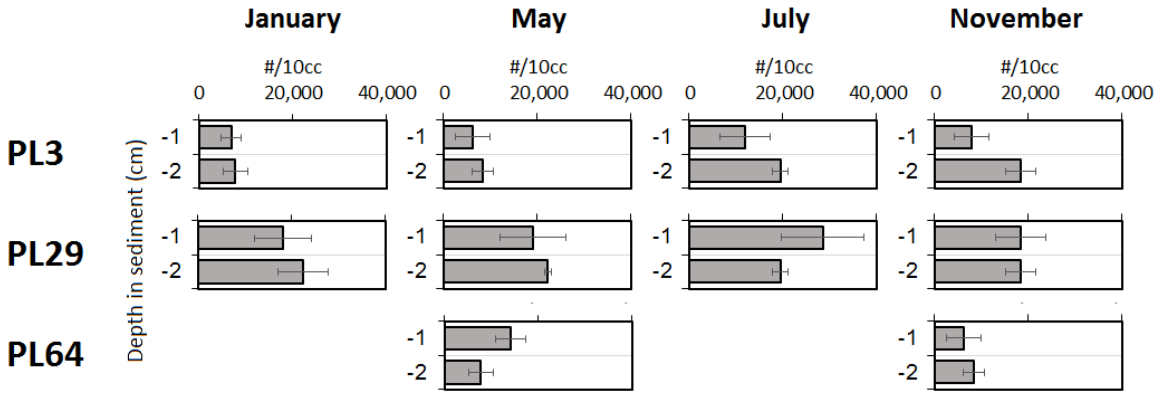


Figure 3.3.2: In-sediment distribution of dead foraminifera per 10cc at PL3, PL29 and PL64. Note PL64 was sampled only twice a year (May and November).

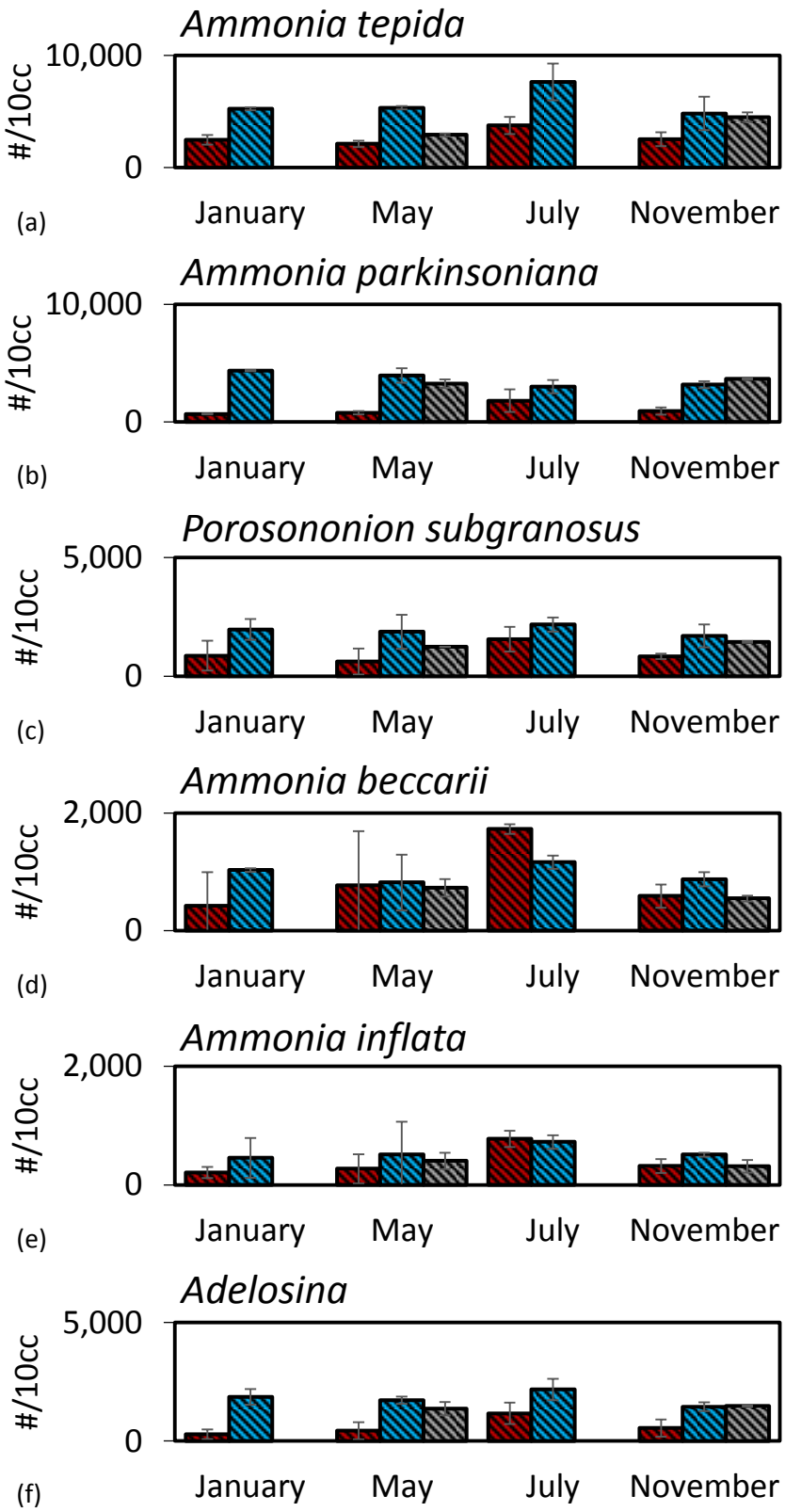


Figure 3.3.3: Seasonal variation in numerical abundance per 10cc (summed over the top 2 cm) of selected species at the three sampling stations during 2012. Note change of scale and station PL64 was sampled only twice a year (May and November).

Table 3.3.1: Diversity indexes of dead foraminiferal assemblage and annual relative abundance of the major foraminiferal groups (summed over 0-2 cm) of the three sampling stations			
	PL3	**PL29**	**PL64**
Collected specimens	4,531	4,907	2,199
Total species richness	124	119	102
Margalef index	14.61	13.88	13.12
#/10cc	9,411±3,681	20,888±2,325	15,321±2,015
Average species richness	79±4	80±8	84±2
Average Pielou's Evenness	0.66±0.01	0.67±0.02	0.66±0.01
Perforate calcareous (%)	83±3%	76±1%	74±1%
Miliolids (%)	14±3%	17±1.3%	20±1%
Organically-cemented agglutinants (%)	1.6±0.7%	4.6±0.4%	3.2±0.4%
Carbonate-cemented agglutinants (%)	1.7±0.7%	2.7±0.3%	2±0.1%

Table 3.3.2: Dead assemblage -- six most common foraminiferal taxa at the three sampling stations.		
PL3	PL29	PL64
Ammonia tepida (30±4%)	*Ammonia tepida* (27±3%)	*Ammonia tepida* (24±4%)
Ammonia parkinsoniana (11±1%)	*Ammonia parkinsoniana* (18±4%)	*Ammonia parkinsoniana* (23±1%)
Porosononion subgranosus (10±1.5%)	*Porosononion subgranosus* (9±0.3%)	*Porosononion subgranosus* (9±0.2%)
Ammonia beccarii (9±2.7%)	*Adelosina* spp. (9±0.6%)	*Adelosina* spp. (9±0.7%)
Adelosina spp. (6±1.7%)	*Ammonia beccarii* (5±0.5%)	*Ammonia beccarii* (4±1.4%)
Ammonia inflata (4±1%)	*Ammonia inflata* (3±0.3%)	*Ammonia inflata* (2±0.7%)

Table 3.3.3: Proportion of deformed tests of selected species at the top cm in three sampling stations.			
	PL3	PL29	PL64
Ammonia parkinsoniana	18.7±2.2%	17.9±3.5%	8.3±3.6%
Ammonia tepida	20±1.3%	17.9±4.4%	7.2±0.4%
Bolivina spp.	36.7±13.7%	18.2±15.1%	15.9±21.2%

3.4. Statistical analysis

Relationship between sampling stations and environmental variables -Principal component analysis (PCA) was conducted in order to determine the relationship between environmental parameters and their effect on the variability of the samples (stations) shown in Figure 3.4.1.

The first two principal components explain 80% of the total variance. On PC1, TOC, temperature and salinity are loaded positively while grain size and oxygen are loaded negatively. Bottom water Chl-water and Chl-sediment are loaded positively on PC2 while temperature and salinity are loaded negatively. Two main trends were clear from the PCA plot temperature & salinity – O_2 concentration and TOC - grain size, each with inverse correlation.

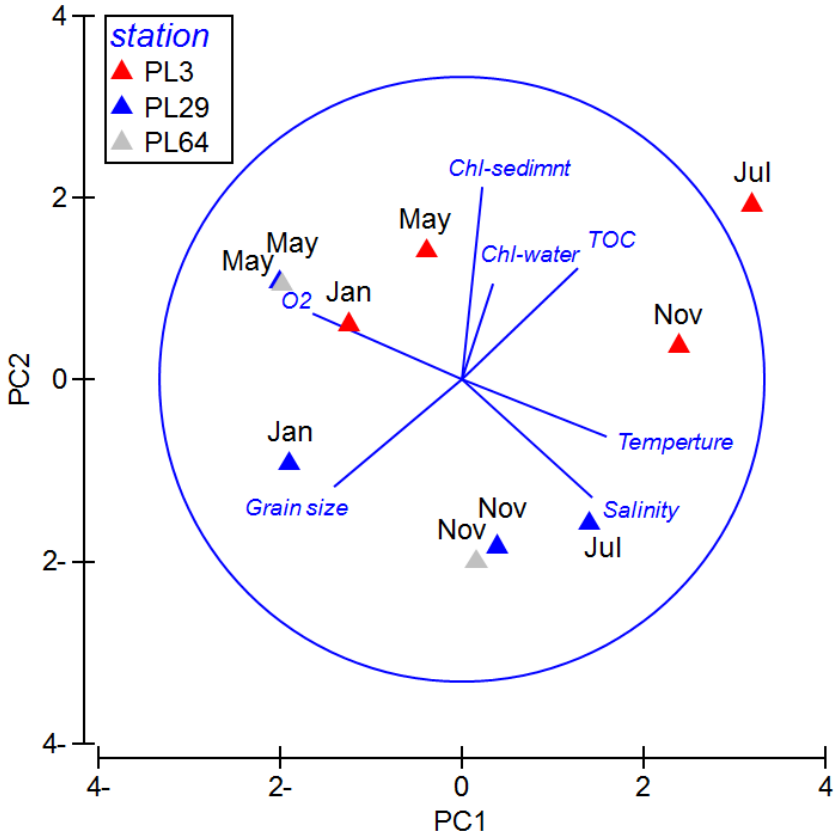
Live assemblage - Cluster analysis was conducted in order to test similarity in community composition between the three sampling stations (Figure 3.4.2). In 20% similarity, two clusters of samples formed. Cluster A is composed exclusively of samples from station PL3 from all sampling seasons, grouped into two sub-clusters: Cluster A1 composed of samples collected during January (55% similarity) and Cluster A2 (samples collected the rest of the year; 40% similarity). The second cluster consists of clusters B and C. Cluster B (samples from station PL29 exclusively, including all samples collected during July; 50% similarity) and cluster C (mixture of samples from stations PL29 and PL64, including all samples collected during May; 45% similarity).

According to the Two-Way Nested statistical analysis of similarities (ANOSIM) shown in Table 3.4.1, a significant difference was found both between seasons across all station groups, as well as between stations. A pairwise test showed that only the

difference between stations PL3 and PL29 is significant, further explanation regarding the inconclusive results from the comparison to PL64 will be given in chapter 4.2.

In order to identify similar behavioral patterns among selected species a cluster analysis (not shown) and non-metric multidimensional scaling (nMDS) plot were conducted compering numerical abundance per 10 cc of ten selected species of the top cm from all three stations (Figure 3.4.3). Results of the cluster analysis at 35% and 55% similarity were marked as circles on the nMDS plot. Two groups of samples were formed at similarity of 35%. Group A is composed of two species (*Adercotryma glomerata* and *Verneuilinulla advena*) with insignificant differences between them. The second group is composed of eight species including the three most dominant species at each sampling station. At less than 55% similarity, two sub-groups signed as B1 (*A. tepida*, *B. striatula*, *Q. bosciana* and *E. scaber*) and B2 (*Bolivina* spp., *F. acuta, A. mariea* and *L. scotti*) emerged.

Dead assemblage – similar to the living community a multivariate statistical analysis of the dead assemblage was conducted with cluster analysis as graphical display (Figure 3.4.4). Two clusters of samples were formed under <50% similarity. Cluster A consists mostly of samples from stations PL29 and PL64 accompanied by four samples of station PL3 (collected during summer and fall), subdivided into two groups (A1 and A2 at 66% similarity). Cluster B composed exclusively of samples from station PL3, grouped into two clusters (B1 and B2 at 65% similarity). As shown in Table 3.4.2, the difference between seasons according to ANOSIM test was insignificant, while a significant difference was observed between stations. The pairwise test showed that there were significant differences between stations PL29 and PL3, as opposed to the insignificant difference between stations PL29 and PL64, for the comparison of station PL3 to PL64 the result was inconclusive (Table 3.4.2). Further explanation regarding these inconclusive results will be given in chapter 4.3.



Eigenvalues

PC	Eigenvalues	%Variation	Cum.%Variation
1	3.47	49.5	49.5
2	2.14	30.6	80.1
3	1.03	14.7	94.8
4	0.239	3.4	98.2
5	7.58E-2	1.1	99.3

Eigenvectors

(Coefficients in the linear combinations of variables making up PC's)

Variable	PC1	PC2	PC3	PC4	PC5
Grain size	-0.425	-0.355	-0.229	0.238	0.596
Chl-sedimnt	0.066	0.634	0.006	0.714	0.042
TOC	0.383	0.368	0.369	-0.401	0.449
Temperture	0.477	-0.189	-0.317	0.301	-0.279
Salinity	0.432	-0.391	0.089	0.003	-0.179
O2	-0.493	0.217	0.085	-0.205	-0.572
Chl-water	0.102	0.317	-0.834	-0.373	0.064

Figure 3.4.1: Two-dimensional PCA ordination of log transformed environmental parameters of bottom water (Temperature, Salinity, O_2 concentration and Chl -water) and top sediment layer (TOC, mode grain size and Chl -sediment) after normalization from the 3 sampling stations.

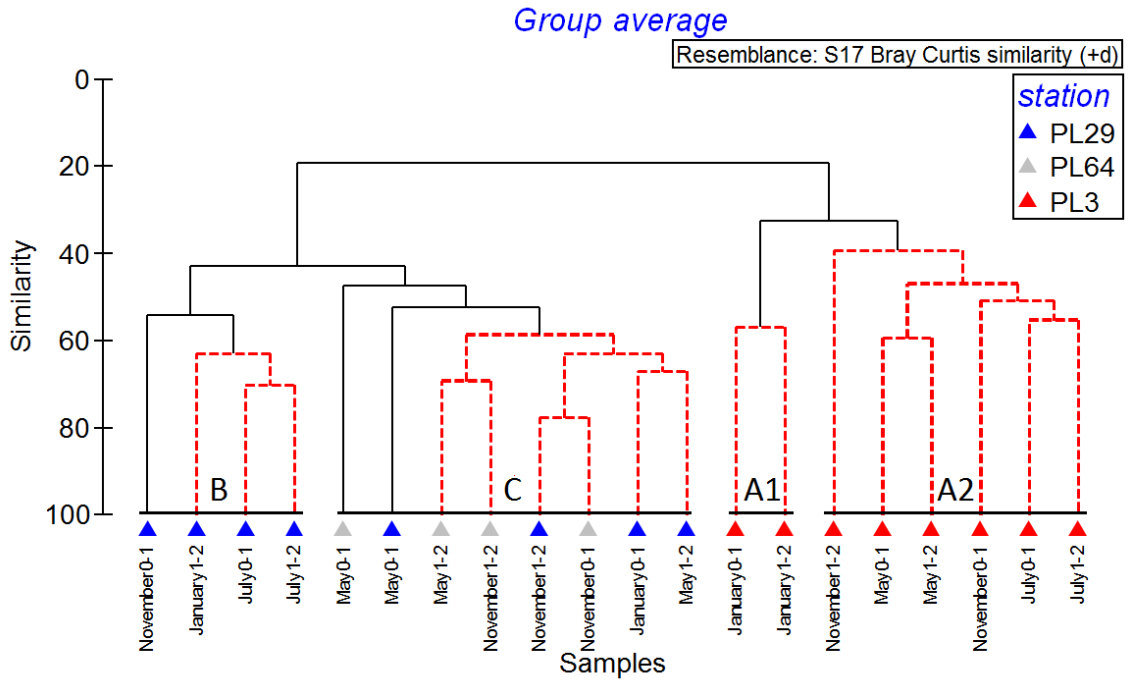
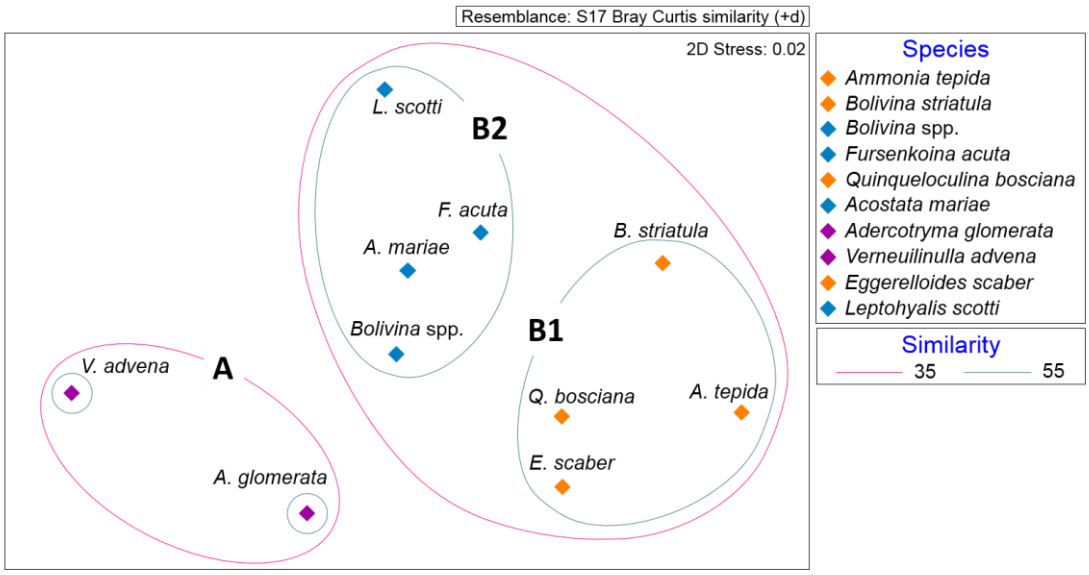


Figure 3.4.2: Dendogram classification of samples produced by Q-mode cluster analysis using Bray-Curtis similarity. Living community numerical abundance of each species per 10cc of the top 0-1 and 1-2 cm of sediment (replicate samples were pooled), at the three sampling stations.



Best 2-d configuration (Stress: 0.02)

Sample	1	2	%
A. tepida	1.30	-0.32	11.3
B. striatula	0.94	0.37	22.2
Bolivina spp.	-0.28	-0.05	17.5
F. acuta	0.11	0.51	9.6
Q. bosciana	0.47	-0.33	7.5
A. mariae	-0.23	0.33	2.4
A. glomerata	-0.69	-0.78	5.1
V. advena	-1.76	-0.23	1.9
E. scaber	0.48	-0.66	15.7
L. scotti	-0.33	1.16	6.7

Figure 3.4.3: nMDS plot of selected species numerical abundance (10 cc). Samples of the upper cm from the three sampling stations; replicates were pooled. The two types of ellipses circle species with 35 and 55% similarity.

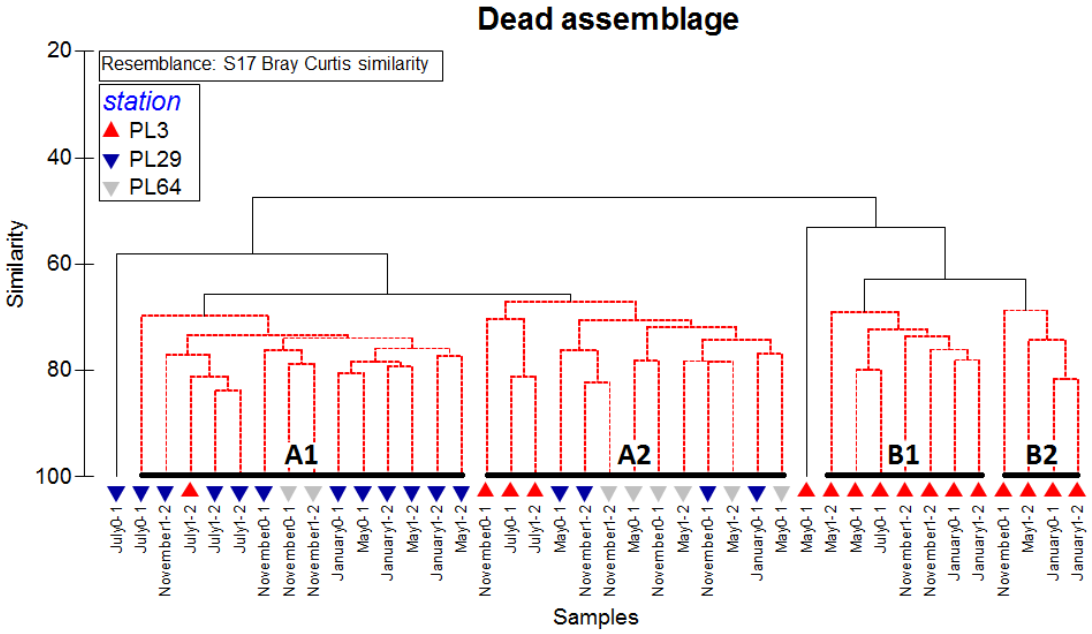


Figure 3.4.4: Dendogram classification of samples produced by Q-mode cluster analysis using Bray-Curtis similarity. Dead assemblage numerical abundance of each species per 10cc at the top 0-1 and 1-2 cm of sediment, at the three sampling stations.

Table 3.4.1: Living community -- statistical analysis of similarities (ANOSIM) followed by pairwise test to determine the difference between each two samples. Significant values in bold.		
	R statist	P value
Difference between seasons	**0.407**	**≤0.01**
Difference between stations	**0.738**	**≤0.01**
Difference between PL3 & PL29	**0.938**	**<0.05**
Difference between PL3 & PL64	0.6679	0.133
Difference between PL29 & PL64	0.661	0.067

Table 3.4.2: Dead assemblage -- statistical analysis of similarities (ANOSIM) followed by pairwise test to determine the difference between each two stations. Significant values in bold.		
	R statist	P value
Difference between seasons	0.108	0.08
Difference between Stations	**0.606**	**≤0.01**
Difference between PL3 & PL29	**0.833**	**<0.05**
Difference between PL3 & PL64	0.643	0.067
Difference between PL29 & PL64	0.429	0.133

4. DISCUSSION

4.1. Changes in environmental parameters over the past decade

4.1.1. Water column

The seasonal pattern at ~ 35 m water depth at the Shafdan site was characterized for the first time by Hyams (2006). The current study aimed to compare the environmental parameters of Hyams (2006) with the regime 10 years later. The sampling year of 2012 was extremely stormy except for May to July, with a strong current regime all year long and high frequency of deep mixing events (Israel Oceanographic and Limnological Research, Haifa, unpublished data), causing changes in distribution of suspended sewage sludge material. During spring, summer and fall 2003-4, a wide sludge spot was detected at PL3 on the sea surface, but in 2012, extension of stormy weather into the spring and high current velocities caused changes in the size and position of the sludge spot, compared to the earlier years characterized by four distinct seasons.

Seasonal variation was observed in both sea surface temperature (SST) and salinity values with lowest temperature and salinity of 17°C and 38.9 psu respectively during winter and up to 30°C and 39.6 psu during summer (Figure 3.1.1). The difference in salinity values of 0.15 psu between station PL3 and the remote stations, PL29 and PL64 during spring may have been due to the three week-delay in sampling of those stations. The water column in the area was well mixed most of the year with distinct stratification of 3-4°C and up to 0.2 psu during spring. The thermocline and halocline were detected at ~20 m water depth (Figure 3.1.1). A similar seasonal pattern of SST and salinity was detected during 2003-4 by Hyams-Kaphzan et al. (2009). The bottom water at all sampling stations was consistently oxic, and O_2 concentration was inversely correlated with temperature. The lower O_2 concentrations in spring were measured only at PL3, as compared to PL29 and PL64 (Figure 3.1.2), as a result of organic matter enrichment by the activated sewage sludge accumulating on the sea floor. The degradation of the sludge consumed the oxygen in the water column, leading to depleted oxygen values during spring, but higher values during winter when no sludge is on the sea floor. A similar pattern of lower oxygen concentration at PL3 was recorded during spring 2004 (Hyams, 2006) with smaller difference between stations. The Chl *a* concentration in the bottom water column followed the temperature cycle, with low concentration during winter increasing with increased temperature up to >6µg/L during summer (Figure 3.1.3). Increased photosynthetic activity as implied from increased Chl *a* during spring and

summer, can decrease the oxygen concentration in the water column especially due to algal respiration during night hours, or intensive bacterial activity. In general the seasonal cycle of 2012 resembled the 2003-4 cycle as described by Hyams (2006) and Hyams-Kaphzan et al. (2009), although maximal Chl *a* concentration in 2003-4 was recorded during late winter and early spring, as opposed to a summer peak of this study. Algae as well as a cyanobacterial summer bloom (reflected as increasing Chl *a*), can occur as a result of an extremely stormy year (as 2012) due to high nutrient circulation even during summer and additional donation from the sediment (Rahav E., IOLR, personal communication, 2015). In 2003-4 an increase in nutrient concentration was noted during summer (Hyams-Kaphzan et al., 2009). Although the nutrient concentration was not measured in the current study, measurements in the same stations during spring and fall (Kress et al. (2013) found the PO_4 concentration to be elevated in station PL3 in both seasons and similar to values measured in 2003-4.

4.1.2. The sea floor

Sediment properties differ between the eutrophic station PL3 and the other two remote oligotrophic stations, PL29 and PL64. At the latter station a coarse-grained size mode was found throughout the year with no seasonal or vertical (to 5 cm in sediment depth) change, low Chl *a* and TOC concentrations, increasing during spring (Chl *a*) and summer (TOC) after mixing of the water column during winter and enrichment of the water column with nutrients (Kress et al., 2013). Accumulation of Chl *a* on the sea floor during spring led to high TOC values during summer. At station PL3 the parameters in the top sediment layer vary seasonally; winter-spring were characterized by coarser grain size and lower TOC values (>99 µm, <1.7 wt.% respectively; Figure 3.1.5, 3.1.6) due to sludge winnowing by currents. No sludge accumulated on the sea floor during those months. Highest Chl *a* and TOC concentrations were measured during spring and summer when sludge began to accumulate on the sea floor. The seasonal variation of organic matter concentration at station PL3 was not shown in the IOLR-Haifa annual monitoring. Instead 4-6 cm of sludge and average value of 2.8 wt.% were recorded (Kress et al., 2013) while the TOC at the remote stations resembled the current study. Most of the year the sediment grain size was similar through the top 5 cm of the sediment (Figure 3.1.5), but during summer the coarser grain size was found deeper in the sediment as a result of sludge accumulation in the upper 2 cm of sediment. In spring, a gradual decrease in grain

size with depth appeared indicating a grain size fractionation process. One explanation for such phenomena is that when grains of different sizes are mixed, finer grains will fill spaces between coarser grains. In this case the intense sediment mixing that led to fractionation was probably due to high abundance of bioturbating worms. According to the long-term annual monitoring of IOLR-Haifa, high abundance of polychaete worms was recorded during spring 2012 (Kress et al., 2013). Extremely high numbers of polychaete worms, in particular the opportunistic *Capitellidae*, have been described in this station especially during spring (Kress et al., 2004; Hyams-Kaphzan et al., 2009).

The correlation between the environmental parameters is best shown by the environmental PCA plot (Figure 3.4.1), two main trends of inverse correlation were detected: (1) TOC vs. grain size; the finer grains usually characterizing the sludge and therefore correlate to high concentration of organic matter. The reverse was recorded in the winter, with coarser grains usually accompanied by low TOC, due to sludge dispersal after winter storms. (2) Temperature & salinity vs. O_2 concentration, the concentration of dissolved oxygen is controlled by sea surface temperature and deep water column mixing. The salinity values highly correlate with temperature values. In addition the Chl *a*-water was correlated with Chl *a*-sediment however, the latter had a larger effect on spring and summer samples at PL3.

The three parameters: grain size, TOC and Chl *a*-water and sediment show the same trend observed by Hyams (2006), 10 years earlier, with elevated TOC and Chl *a* concentrations during summer and fall, although the concentrations were 1.5-3 times higher during 2003-4 in station PL3, while during spring the TOC was lower by an order of magnitude in 2012 comparing to 2003. The grain size distribution pattern indicates that the measured mode in this study increased by ~20 µm over the last 10 years. This may be a continued long-term effect of the damming of the Nile in the last century (1965), that prevented almost completely the discharge of fines to the Mediterranean, mostly affecting the Levantine basin, causing a 5-10 -fold increase in percentage of particles >63 µm in the sediment (Almogi-Labin et al., 2009). In conclusion, the decrease in nutrient flux that started 5000 years ago with the transition to an arid climate (Tapiero, 2002) was magnified by the damming of the Nile River in the last century, as opposed to sewage sludge injection that resulted in a local organic material enrichment.

4.2. The local live assemblage

4.2.1. Live benthic foraminiferal assemblage characteristics

The main findings are as follows:

A. **Eutrophic site - station PL3** is characterized by low seasonal variation, extremely low TSS followed by low species richness, high evenness, as well as a shallower average living depth (0.6-1.9 cm) within the sediment compared with the other stations.
B. **Oligotrophic site - station PL29** is characterized by high winter-summer variation, high values of TSS, species richness and evenness. Specimens were found alive up to 5 cm depth within the sediment, deeper layers were not examined.
C. **Oligotrophic site - station PL64** is characterized by low seasonality effect, moderate values of TSS, high species richness, and high evenness. Specimens were found alive up to 5 cm depth within the sediment, deeper layers were not examined.

At station PL3 only a few specimens were found alive in the top 5 cm of the sediment, as compared to >60 specimens/10cc at station PL29 and >30 specimens per 10cc at PL64, the densities at the top cm were slightly higher with <50 specimens/10cc at PL3, <210 and <70 at PL29 and PL64 respectively (Table 3.2.1), much lower densities compared to 100-1200 specimens/10cc recorded in the top 2 cm off Bet Yanai at 40m water depth (Jannink, 2001). In the current study, densities were considered low, but within the normal range for the ultra-oligotrophic shallow shelf (Murray, 2006). Such a depleted foraminiferal assemblage close to the sewage outfall (PL3), elevated TSS values in somewhat enriched areas (PL29), falling off to a normal unaffected background, has been documented previously (Yanko et al., 1994; Alve et al., 1995; Loubere & Fariduddin, 1999). The same pattern is shown by polychaete worms in the fall, which had extremely low numerical abundances in the vicinity of the outfall, flourished at some distance from the outlet, falling off to lower numbers in the clean remote stations (Kress et al., 2004 & 2013). Extremely low TSS values at station PL3 is consistent for all sampling seasons, implying environmental stress (Hyams-Kaphzan et al., 2009).

The present study does not show the low species richness and high dominance of *Ammonia tepida* found 10 years ago (Hyams-Kaphzan et al., 2009). Patchy distribution of this species might explain this difference, although that is highly unlikely since replicate samples were analyzed in the current study (duplicate at stations PL29 and PL64 and triplicate at PL3). High evenness at PL3 (Table 3.2.1) can be attributed to reduction of

~40% in heavy metal concentrations over the past 10 years (Kress et al., 2013) or by the many stormy events during 2012, that led to better aeriation of the sediment making this station less stressful, enabling colonization by less opportunistic species. Stations PL29 and PL64 shared more than 75% of the common species, the majority (>50%) absent at station PL3. The most common species *A. tepida*, *Bolivina striatula* and *Eggerelloides scaber* in all three sampling stations (Table 3.2.2), likely represent a common pool of species, but relative abundances were not similar due to intermittent organic material enrichment in recent years.

Multivariate statistical analysis (Figure 3.4.2 and Table 3.4.1) showed that similarity in community composition between and within stations increases with distance from the pollution source. The high variability within samples from station PL3 (40% similarity within the main group; Figure 3.4.2) is attributed to a patchy, non-homogenized unstable sea floor. The ANOSIM test similarly indicated that station PL3 was significantly different from station PL29 ($R=0.938$, $P<0.05$; Table 3.4.1), while no significant differences were found between PL29 and PL64. Similar results were obtained from the annual monitoring of macrofauna of 2012 in the fall (September), where low infaunal abundances and species richness were found up to 3 km north of the outfall, compared with significantly higher diversity in the remote stations (Kress et al., 2013). The inconclusive difference quotient between stations PL3 and PL64 is unreasonable, and was probably due to insufficient number of samples and replicates at PL64, since this station was sampled only twice (see Clarke and Warwick, 1994).

4.2.2. Seasonal pattern in live foraminiferal community

Seasonal variation in foraminiferal community structure as a result of high turnover rate is reflected in the quick response to seasonal environmental change. Reproduction usually occurs in spring following the phytoplankton bloom cycle (Schönfeld et al., 2012). At station PL3, elevated foraminiferal TSS and species richness of winter compared to the rest of the year (Figures 3.2.1a, 3.2.4), also observed 10 years earlier (Hyams-Kaphzan et al., 2009) is explained by removal of sludge and aeration of the sediment by winter storms. This suggest that the polluted station PL3, is least contaminated during winter when sludge is dispersed, organic matter decreases to 1.64±0.04%, and oxygen level

increases, although the maximal ALD was found during spring (1.7±1.2 cm) when live specimens were found as deep as 5 cm into the sediment (Figure 3.2.4).

Changes in depth penetration between seasons can be explained according to the TROX model, in which food supply, oxygen levels and the effect of the redox zones are the most important factors controlling the microhabitat of benthic foraminifera in deep sea environments (Jorissen et al., 1995; De Stigter, 1996; Van der Zwaan et al., 1999). Under natural conditions, foraminifera can be found alive down to 10 cm in sediment depth (Jorissen, 1999) as found in all samples of station PL29 during 2003-4 (Hyams-Kaphzan et al., 2009). The deep penetration depth of a few species down to 5 cm at PL3 during spring was also found 10 years ago during the same season (Hyams-Kaphzan et al., 2009) and may be explained by vertical transport as a result of bioturbation by polychaete worms that were extremely abundant in the area during this season (Kress et al., 2004; Hyams-Kaphzan et al., 2009). An alternative explanation might be the slower cytoplasm degradation under low oxygen concentrations, such as that Rose Bengal stains also dead foraminiferal tests (Bernhard & Sen Gupta, 1999). This explanation is less reasonable since stained specimens were only observed in the lower sediment layers during spring, therefor this phenomena probably relates to the bioturbation and ventilation of the sediment in the same season.

Samples of stations PL29 and PL64 showed a very weak variation in foraminiferal TSS and species richness when summed over the top 5 cm (Figure 3.2.1b-c), while a prominent difference was found in the distribution of specimens with depth, that together with the seasonal variation in foraminiferal ALD (Figure 3.2.4) suggesting a seasonal migration of specimens between sediment layers. The statistical test (ANOSIM) showed that at the top 2 cm of sediment the seasonal variation in foraminiferal community was significant ($R=0.407$, $P \leq 0.01$; Table 3.4.1). Living individuals were found down to 5 cm in the sediment, with highest abundance in the top 2 cm.

4.2.3. Community composition of live benthic foraminifera (Table 3.2.2, Figures 3.2.2, 3.4.3)

The main findings are as follows:

PL3 is dominated by *E. scaber* - *Acostata mariae* – *A. tepida* – *B. striatula* (representing together >30%).

PL29 is dominated by *A. tepida* - *B. striatula* - *E. scaber* – *Quinqueloculina bosciana* (representing together >50%).

PL64 is dominated by *A. tepida* - *B. striatula* - *E. scaber* – *Ammonia parkinsoniana* (representing together >45%).

In anthropogenically polluted areas there generally seems to be a shift in community structure to high dominance of opportunistic species, as well as decreasing abundance of the natural inhabitant species until total disappearance (Loubere & Fariduddin, 1999). This pattern was shown in the Punta Carretas zone at Montevideo Bay, Uruguay where the species *A. tepida* dominated 99% of the polluted assemblage (Burone et al., 2006). Therefore patterns of appearance and disappearance of species between adjacent stations is very important for detecting environmental change. Some species have a reputation as bioindicators for polluted environments, including high tolerance to oxygen depletion, e.g. *A. tepida, E. scaber, Bulimina marginata, Bolivina* spp. (mainly *Bolivina seminuda, Bolivina dilatata* and *Bolivina spathulata*) and *Verneuilinulla advena* (e.g. Ernst et al., 2005; Murray, 2006). Other species respond very quickly to enrichment of organic material as a food resource, such as *Caronia silvestrii, Eilohedra vitrea, A. mariae* and *Hopkinsina pacifica* and to some extent *Nonionella turgida* (=*Nonionoides turgida*) (Ernst et al., 2005), and *Reophax*, *Adercotryma, Epistominella* and *Fursenkoina* all feed off organic detritus (Murray, 2006). All of those species were found at all three sampling stations in the current study but in different relative abundances.

At station PL3, *E. scaber* and *A. mariae* had higher relative abundance (14% and 7% respectively) than at the remote station (Table 3.2.2), and all dominant species (>5%) had higher abundances during winter, when the total TSS was 6-7 times higher than the rest of the year (Figure 3.2.3). At PL29 and PL64, the most dominant species (>5%) *A. tepida*, *B. striatula Q, bosciana* and *E. scaber* were grouped together (cluster B1) according to the selected species nMDS (Figure 3.4.3) with elevated TSS all year long, but especially during summer and fall (Figure 3.2.3). *Bolivina* spp. (all *Bolivina* species besides *B. striatula*), *Fursenkoina acuta, A. mariea* and *Leptohalysis scotti* (Group B2 in the selected species

nMDS; Figure 3.4.3) are all known as organic material detritivores that occur in high numbers in the surface layer (Barmawidjaja et al., 1992; Ernst et al., 2005; Murray, 2006). They showed some degree of patchiness and inconsistency in their numerical abundance, with elevated numbers especially during spring (and to some extent summer). All the seven species mentioned above have some association with anthropogenic pollution and high organic flux. Other less common species such as *Buliminella elegantissima, B. marginata, Epistominella vitrea (=E. vitrea), N. turgida* and *V. advena* were also frequently found near sewage outfalls (e.g. Mojtahid, 2008; Burone et al., 2006; Vilela et al., 2004; Frontalini & Coccioni, 2008).

4.2.4. Vertical distribution of selected species (Figures 3.2.5-3.2.7)

Jorissen (1999) suggested four types of in-sediment distribution profiles: Type A (epifaunal or shallow infaunal) are restricted to the top 0-1 cm, sometimes with a few individuals found deeper in the sediment. Type B (shallow infaunal or transitional) occurred in high numbers over several cm, not restricted to the uppermost cm, and were found usually in association with a coarse-grained shallow substrate where sediment is intensely burrowed to a considerable depth. Type C (intermediate or deep infaunal) shows low abundance in the top sediment and one or more maxima deeper in the sediment. Type D is a combination of high abundance on the surface and one or more additional maxima deeper in the sediment.

Ammonia tepida, the most common species in station PL29 and PL64, is known as an opportunistic species associated with anthropogenic pollution (e.g. Vilela et al., 2004; Yanko et al., 1999). It follows a type A distribution profile at station PL3, and high numbers throughout the top 5 cm (types B and D) at station PL29 and PL64.

Eggerelloides scaber is the most common species in station PL3, showing a type A distribution profile. This species shows mainly a type C distribution profile at stations PL29 and PL64, with some variation in the fall.

Other species such as *B. striatula*, *F. acuta*, *Q. bosciana*, *A. mariea* and *L. scotti* had type A distribution pattern with surface maxima most of the year in all three stations. There is some variation in the winter subsurface at PL29 and PL3 for *B. striatula*, this species also showed type B distribution at PL64.

In general, at the unpolluted stations PL29 and PL64, the dominant species could be separated into two distinct groups: epifaunal species (e.g. *F. acuta*, *A. mariea and L.*

scotti) that were found in large numbers in the sub-surface only when oxygen concentration in the bottom water column peaked and TOC in the sediment surface was lowest (winter). The second group consists of infaunal species (*A. tepida* and *E. scaber*) found most of the year in the surface layer as well as deeper in the sediment, as opposed to *A. tepida* proliferation in the top 2 cm during summer and fall of 2003 that was not found in the current study. The deep sediment preference may be related either to organic material enrichment with depth, or escape from potential predation pressure. At station PL3 all species showed a distinct preference for the upper cm, including species that occurred deeper in the sediment at the remote stations. This is explained by organic material accumulating on the surface decreasing downward (mainly during summer and fall; Figure 3.1.5d) and low oxygen concentration at depth. Migration of foraminifera towards higher oxygen availability is not exceptional (Murray, 2006).

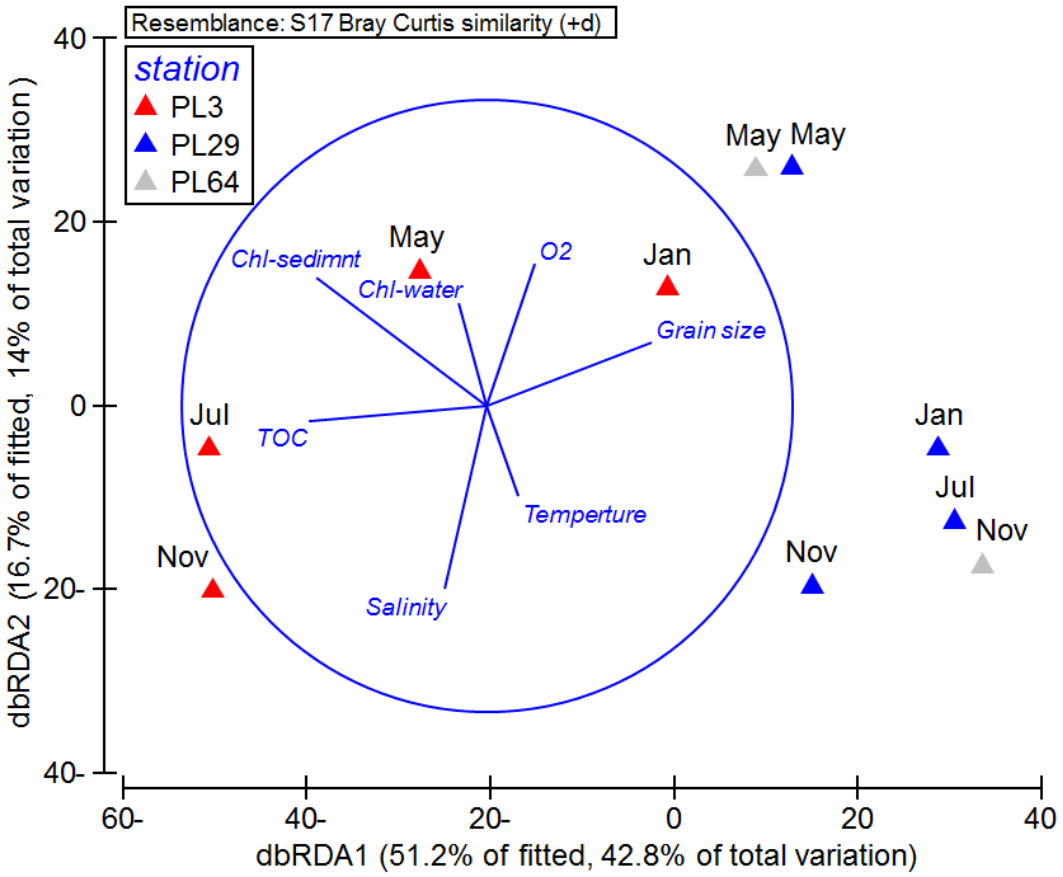
4.2.5. Foraminiferal response to environmental conditions

The measured environmental parameters in the water column showed similar seasonal cycles in all three stations but lower oxygen concentration in the spring at station PL3 (Figures 3.1.2). The main differences between the three stations were in sediment properties with up to 3 times higher TOC, Chl-a sediment concentrations, and decreased grain size mode especially during summer and fall at station PL3, compared with the remote stations (PL29 and PL64) (Figures 3.1.5-7). The eutrophic trajectory between the polluted - stressed PL3 station and the oligotrophic PL29 and PL64 stations was therefore tracked by the foraminiferal community in the top 5 cm, with a dramatic decrease in both TSS and species richness at station PL3 at all sampling seasons (Table 3.2.1, Figure 3.2.1). In order to determine which environmental parameters correlate with the foraminiferal abundance and composition two statistical tests were conducted. BEST analysis showed a significant (p=1%) high (Rho: 0.774) correlation, the “best fit” was achieved when only grain size, Chl-sediment and TOC values were included in the analysis. Moreover, the correlation was highest when only TOC parameter was included (Rho: 0.750) indicating it is probably the most influential parameter. This was also strengthened by the results of the distance-based linear model (disTLM) showed that the same three parameters are significant and when each one of them is considered by itself, TOC indeed explained most of the variation (38%). The second contributor was the grain size parameter (36%) and the third was Chl-sediment (29%). When all seven

environmental parameters are included, using a sequential test, they explain 84% of the variation of foraminiferal abundances in all sampling stations. The graphical display of this statistical test is presented in Figure 4.2.1 as a dbRDA in which the first two axes explain 68% of the fitted variation, which compose about 57% of the total variation in the resemblance matrix.

The correlation between total organic matter (TOC) and live foraminiferal numerical abundance in the upper cm is shown in Figures 4.2.2 (PL3) and 4.2.3 (PL29). At station PL3 total organic carbon (TOC) concentration was about 3-8 times higher during summer and fall with up to 3.8±0.4 wt.%, that led to sharply decreased foraminiferal numerical abundance (Figure 4.2.2). Although the decreased abundance was noted in all species, some were affected to a lesser degree including *A. tepida*, *B. striatula* and *E. scaber*, while other species were rarely found during those seasons (e.g. *B. marginata*, *Q. bosciana*, *A. mariae*, *Adercotryma glomerata, Textularia earlandi* etc.) or totally absent (*B. spathulata, H. pacifica, L. scotti* etc.). During spring, the foraminiferal TSS was still very low and relatively low TOC concentration (1.28±0.06%) was measured, that was inconsistent with measurement of TOC (2.78%) conducted two weeks earlier by the IOLR monitoring program. The 4-6 cm layer of sewage sludge once found above the sediment (Kress et al., 2013) was not found in the current study. A non-homogenized seafloor can be reflected in patchy organic material clumps. During the sampling program, spring storm-derived high waves (>1.5 m) may have dispersed sludge from the seafloor and lowered the TOC concentration, although this was considered highly unlikely. It is also possible that activated sewage sludge began to accumulate on the seafloor during spring but was consumed immediately by rapidly multiplying detritus-feeding polychaetes. In fact, opportunistic macrofaunal species at PL3 reacting to organic enrichment in the spring (Kress et al., 2004, 2014; Hyams-Kaphzan et al., 2009), would lead to lower abundances of benthic foraminifera due to competition and predation. This pattern was observed experimentally by Widbom and Frithsen (1995), who suggested that competition for space by a few opportunistic macrofaunal species (such as *Polydora* tube worms), could limit the response of other species within the benthic community. Moodley et al. (1998) showed negative influence on meiofaunal densities by biological interaction with macrofauna. Jannink (2001) found abundant living *Polydora* tube worms in the top sediment layer off Bet Yanai during winter, and at the same time, somewhat lower abundances of benthic foraminifera on the sea floor and a clear sub-surface maximum,

probably as a result of such competition pressure. At PL3 in the spring live foraminiferal specimens were found down to 5 cm with higher numerical abundance and species richness deeper in the sediment, explained by vertical transport by bioturbation, probably by macrofaunal Capitellid worms documented earlier in the season (Kress et al. 2013). Highest species richness occurred here mainly during winter when no sewage sludge accumulated, the TOC concentration was low and highest oxygen concentration was recorded. Hyams (2006) also showed that in 2004 polychaete worms were less abundant at station PL3 during winter, therefor the predation pressure and competition probably decreased. At station PL29 the modest elevated TOC during summer and fall up to a maximum of 0.53±0.09 wt.% cannot explain by itself the sharp increase in live benthic foraminiferal numerical abundance at the top cm (Figure 4.2.3) that was especially noted in the species *A. tepida*, *B. striatula*, *Q. bosciana* and *E. scaber* (Figure 3.2.3). This increasing abundances at the top 2 cm seems to occur as a result of an upward migration of specimens toward the surface during summer and fall (Figure 3.2.4) therefore probably at least partially related to the decrease of ~2mg/L in oxygen concentration at the bottom water (Figure 3.1.2) although oxygen concentration in the sediment was not measured in the current study.



Percentage of variation explained by individual axes

Axis	% explained variation out of fitted model Individual	Cumulative	% explained variation out of total variation Individual	Cumulative
1	51.21	51.21	42.81	42.81
2	16.74	67.96	14	56.81
3	10.69	78.64	8.93	65.74
4	8.51	87.15	7.11	72.86
5	6.51	93.66	5.44	78.3
6	3.6	97.26	3.01	81.31
7	2.74	100	2.29	83.6

Relationships between dbRDA coordinate axes and orthonormal X variables (multiple partial correlations)

Variable	dbRDA1	dbRDA2	dbRDA3	dbRDA4	dbRDA5	dbRDA6	dbRDA7
Grain size	0.538	0.206	-0.689	-0.029	-0.033	-0.402	0.173
Chl-sedimnt	-0.556	0.422	-0.180	0.354	0.230	-0.027	0.549
TOC	-0.582	-0.049	-0.323	-0.648	-0.159	-0.272	-0.187
Temperture	0.102	-0.296	0.384	-0.280	0.491	-0.520	0.406
Salinity	-0.140	-0.600	-0.060	0.357	-0.584	-0.239	0.302
O2	0.155	0.464	0.393	-0.351	-0.571	0.015	0.396
Chl-water	-0.091	0.338	0.288	0.354	-0.112	-0.660	-0.470

Figure 4.2.1: dbRDA plot of the log-transformed environmental parameters in the bottom water column and in the top sediment correlated with pooled abundance data per 10cc of the top sediment layer. Symbols represent stations.

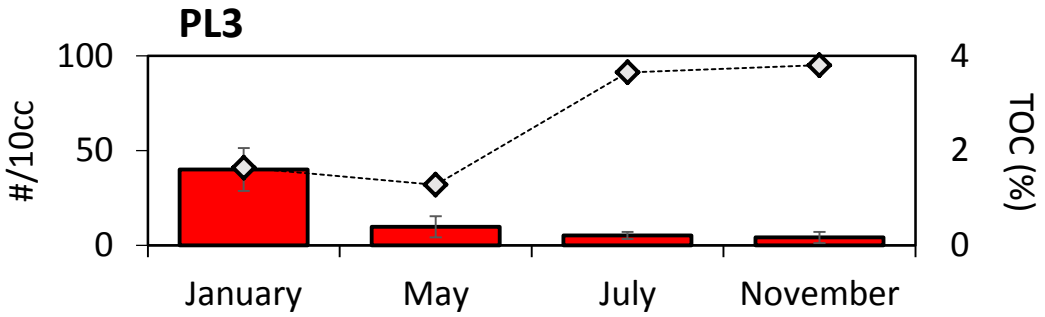


Figure 4.2.2: The foraminiferal TSS (bars; number of specimens per 10 cc), and TOC (diamonds; wt.%) January to November 2012 top cm at station PL3.

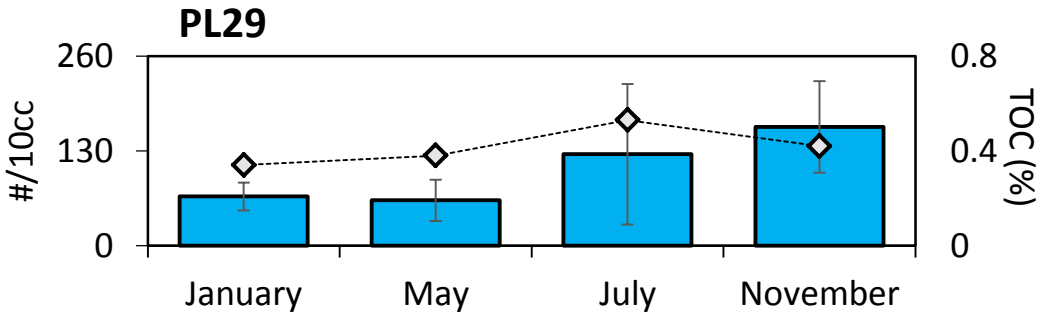


Figure 4.2.3: The foraminiferal TSS (bars; number of specimens per 10 cc), and TOC (diamonds; wt.%) January to November 2012 top cm at station PL29.

4.3. **Changes in foraminiferal community structure over the past 10 years**

The main modifications of the living community during the last 10 years are as follows (comparisons refer to data of Hyams, 2006; Hyams-Kaphzan et al., 2009): **Station PL3** - The changes in diversity indices and dominant species numerical abundance at the top cm between the years 2003 and 2012 is shown in Table 4.3.1. The most dramatic change was the decrease in TSS (per 10cc) in the top cm of ~50%. However, this decrease in foraminiferal numerical abundances does not reflect on species richness itself, but rather on distribution of specimens among different species as calculated by both Margalef and Pilou's evenness indices (Table 4.3.1). This is best seen when all samples are compiled together for the cumulative abundance plot (Figure 4.3.1), with decrease in the relative abundance of the four most common species from >80% in 2003 to 40% in 2012. Decreased dominance, mainly of *A. tepida* (Table 4.3.1) was supplemented by increase in total species richness as a result of >20 new incoming species. Most of those species were present at station PL29 during 2003-4, including *B. striatula* and *H. pacifica,* but some appear for the first time in 2012 (*Bolivina earlandi, Elphidium crispum, Paratrochammina* spp. etc.).

The mixed signals at PL3, were on one hand, TSS decreasing dramatically, but on the other hand, incoming species that were previously only found at the control station PL29 during 2003. PL3 was considered sterile with no living foraminifera during fall of 2003, but contained 33 live specimens during fall of 2012. This change may be attributed to the storm events during 2012, dispersing sludge, causing failure of organic matter to accumulate significantly, and consequently leading to somewhat improved conditions at this station. The only parameter that indicates that this station is still under great stress is the dramatic decrease in foraminiferal TSS. This may be a strong signal of long-term deterioration that is not masked by short-term improvement.

Multivariate statistical analysis based on cluster analysis of samples collected during 2003 and 2012 (only samples of >20 specimens were used) after standardization, is shown in Figure 4.3.2. At 20% similarity two distinct clusters were formed according to the sampling year (2012 vs. 2003). Cluster A (40% similarity) consist of all samples collected during 2012, while cluster B (50% similarity) includes all the samples collected in 2003 (Figure 4.3.2). Similar results were obtained from ANOSIM test (Table 4.3.2) with significant difference between sampling years. In addition, the seasonal pattern that was observed by Hyams-Kaphzan et al. (2009) remained the same during 2012, with highest

TSS and species richness during winter and lower in the rest of the year, as was also seen by the significant differences between samples from different seasons (across all sampling years; Table 4.3.2).

Station PL29 – Changes in diversity indexes and dominant species numerical abundance at the top cm between the years 2003 and 2012 are shown in Table 4.3.3. The sharp decrease in TSS from elevated numbers during 2003 to reduced values during 2012, resulted in decreasing values of species richness although evener distribution of specimens among species was found in all sampling seasons of 2012 as shown from Pilou's evenness, furthermore higher Margalef diversity index was found during summer and fall 2012 compared to 2003-4 (Table 4.3.3). This decrease in dominance was also shown by the cumulative abundance plot, where >60% of the assemblage was represented by three species in 2003 compering to six species in 2012 (Figure 4.3.3). In addition the increase in the total species richness (as seen in Figure 4.3.3) was a result of >30 new species in this station including *Gavelinopsis praegeri*, an epiphytic species, usually found in well-oxygenated environments of low organic matter concentrations and sandy sediment (Altenbach et al., 2003; Martins et al., 2006; Teodoro et al., 2010). Similarly, in 2012 *G. praegeri* was noted in high numbers at Hadera beach rocks at 5 m water depth (~60km north of Palmachim) especially during summer and spring (Wainsztok Y., personal communication, 2015) although it was not found 5 years earlier in the same area (Arieli et al., 2011). In general all faunal indices (numerical abundance per 10cc, species richness, Pilou's Evenness index) as well as decreasing relative abundance of the most dominant species *A. tepida*, *B. seminuda* and *E. scaber* (Table 4.3.3) - all imply an improvement of conditions at this station, which 10 years ago was enriched in organic matter during summer and fall (0.96% and 0.69% respectively) relative to background sites such as Bet-Yanai (Jannink, 2001; Hyams-Kaphzan et al., 2009). The sediment properties track this change, as during summer and fall the TOC decreased by 40% (0.53±0.09% and 0.42±0.01% respectively) to values close to natural background conditions of 0.42%±0.16 (described by Kress et al. (2004) at a control station located 4.5km south of the outfall) that explain the high foraminiferal TSS and dominance decrease. The decrease in organic matter is consistent with the long-term trend of increase in grain size. On the other hand, the differences in Chl a-sediment concentration between years were inconsistent.

As at station PL3, a multivariate statistical analysis of station PL29 samples was conducted on samples in excess of 100 specimens, a square root transformation was conducted in order to prevent *A. tepida* proliferation during 2003 masking the results, taking into account the relative abundance of each species from the top 0-1, 1-2, 2-3, 3-4 and 4-5 cm using cluster analysis (Figure 4.3.4). At 45% similarity two distinct groups emerged: **Group A** includes all samples of 2012. **Groups B1 and B2** (50% similarity each) composed of all samples collected during 2003.

The ANOSIM test shown in Table 4.3.2 verified that there is a significant difference between sampling years. The difference between seasons (across all sampling years) was significant, probably related to the low TSS at the top cm during winter and spring and high abundance during summer and fall (Table 4.3.3).

4.3.1. Response of selected species to environmental change over the past 10 years

The decrease in TSS in both sampling stations between the years 2003-4 to 2012 was mainly due to decreased numerical and relative abundance of the most dominant species, *A. tepida,* as was shown in Figures 4.3.1, 4.3.3 and Table 4.3.1, 4.3.3. Some taxa such as *E. scaber*, *Bolivina* spp. and *Q. bosciana* showed a similar numerical abundance in 2003-4 and 2012 at PL3 and only a weak decrease during 2012 at PL29 (Table 4.3.1, 4.3.3). However, a shift in the main *Bolivina* species occurred, as in 2003-4 the dominant species was *B. seminuda*, while in 2012 this species was rarely found, and instead the species *B. striatula* became dominant in all sampling stations (Table 4.3.4). *Acostata mariea* was the only dominant species that reacted differently at each station. At PL3 this species was rare during winter and spring 2003-4 and absent the rest of the year, while in the current study its numerical abundance doubled and few specimens were even found during summer (Table 4.3.1). The trend at PL3 was opposite to the trend observed at station PL29, with dramatic decrease in abundance of 50% in 2012 during winter and an order of magnitude decrease the rest of the year (Table 4.3.3). In addition this was the only species that changed its living depth. During the sampling years 2003-4, it was restricted to the top cm at PL3 while in 2012 live specimens were found down to 3-4 cm during winter and spring (Figure 3.2.7). It seems that the vertical distribution and abundance of this species correlates to organic matter concentration, with a distinct preference toward moderate enrichment (1-4%), while higher concentration appear to be

fatal, as in 2003 when TOC concentration reached >10%. Additionally >8 cm of sewage sludge accumulated in 2003, compared to <3 cm of sludge in 2012; the IOLR measured 4-6cm during that year but dispersion seems to have been rapid (Kress et al., 2013). One factor likely to control living depth is the oxygen concentration, measured 10 years ago but not measured in the sediment in the current study, and therefore incomparable, while measured values in the water showed all samples fully saturated. *Acostata mariea* is known for its opportunistic behavior, flourishing under high organic matter environments but migrating towards shallower depth habitat when oxygen concentration decreases (Ernst et al., 2005).

In contrast, the better known opportunistic species *A. tepida* showed the most dramatic decrease in numerical abundance between 2003 and 2012, in both stations, and almost disappears from station PL3 (Table 4.3.1, 4.3.3). In 2003-4, *A. tepida* was found in high numbers as deep as 10 cm at the control station (PL29), while 10 years later (2012) relatively high numbers were still found in all 5 cm of sediment, and probably at deeper levels as well, but the overall decrease was dramatic. Furthermore, *A. tepida* continued to be the most dominant species at station PL29, constituting >25% of the assemblage (Table 3.2.2). This relative abundance decrease seems to relate to replacement by other species as inferred from higher Pilou's evenness values in 2012 (Table 4.3.3). According to IOLR monitoring since 2010, the area affected by the sludge decreased and did not reach this station (PL29), also shown by the finding that in the past 10 years (2004-2012) the heavy metal concentrations were reduced by ~40% (Kress et al., 2013). In addition, reduction of organic matter enrichment during summer and fall from 0.96% and 0.69% TOC concentration respectively was noted, close to natural background conditions (0.42%±0.16). The improved conditions at station PL29 can explain the lower numerical abundance of *A. tepida* in 2012.

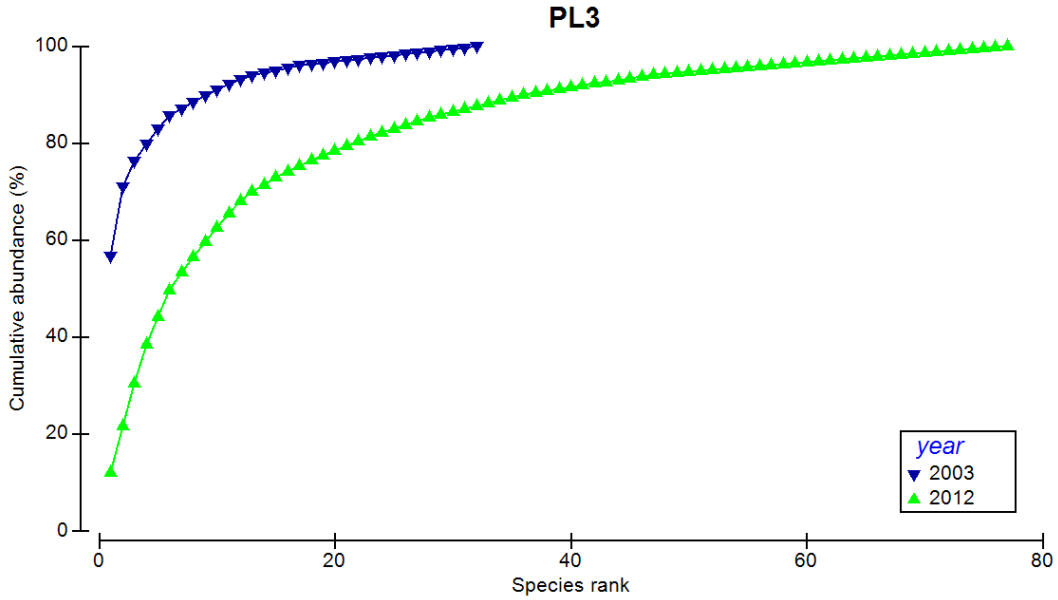


Figure 4.3.1: Average cumulative abundance (%) against ranked species at station PL3 in 2003 and 2012.

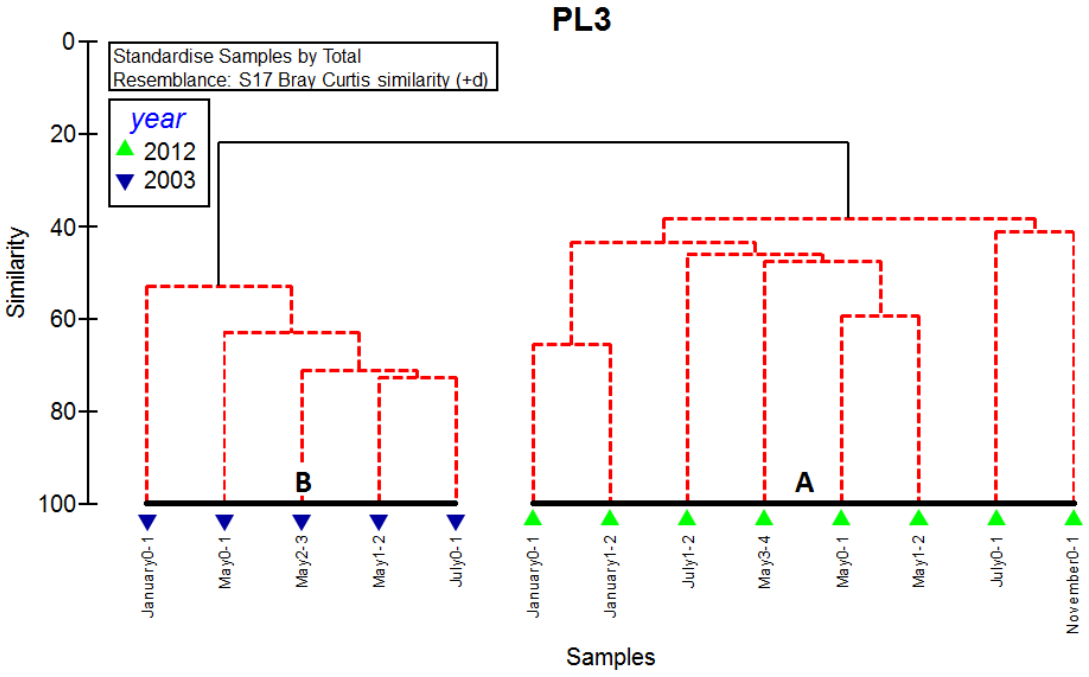


Figure 4.3.2: Dendogram classification of samples produced by Q-mode Cluster analysis using Bray-Curtis similarity. Relative abundance of each species including all samples consist >20 live specimens (replicate samples were pooled together) at station PL3, in 2003 and 2012.

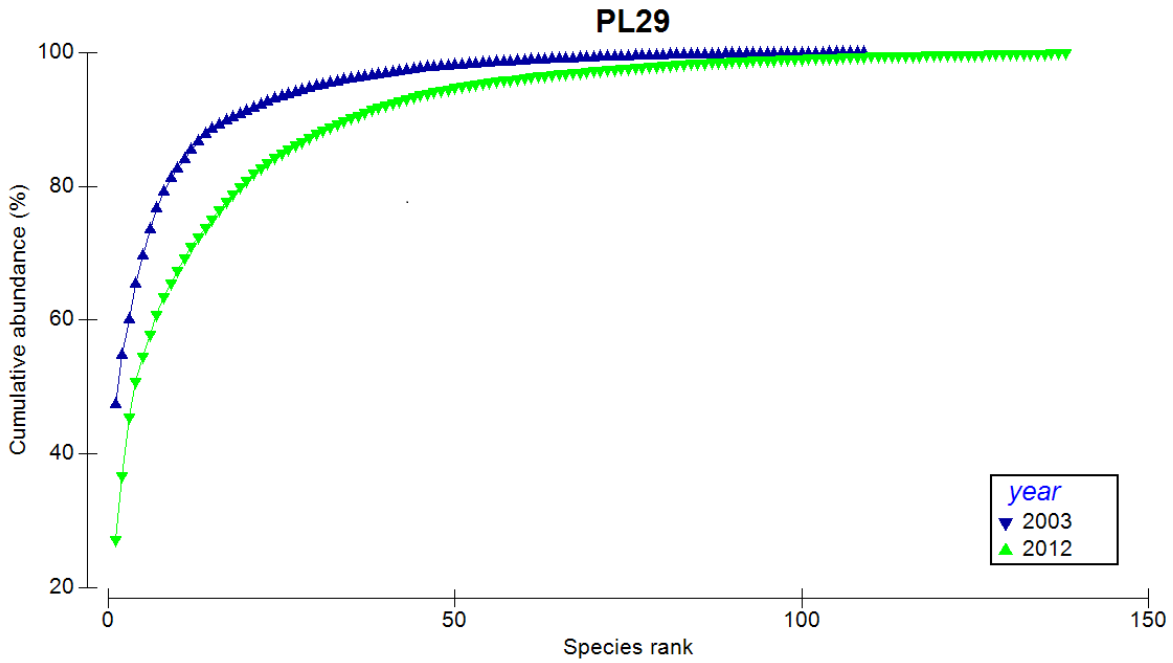


Figure 4.3.3: Average cumulative abundance (%) against ranked species at station PL29 in 2003 and 2012.

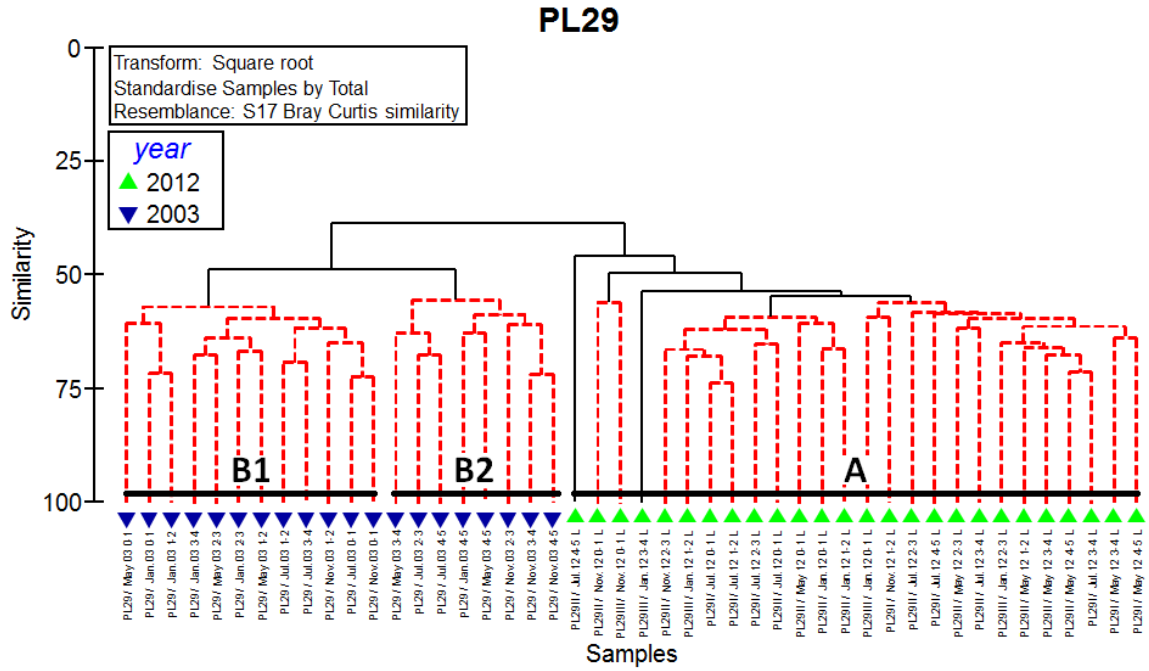


Figure 4.3.4: Dendogram classification of samples produced by Q-mode cluster analysis using Bray-Curtis similarity. Relative abundance of square root transformed samples of the top 5 cm of sediment (only samples of >100 specimens were used) at station PL29, in 2003 and 2012.

Table 4.3.1: Top cm diversity indices and most dominant species numerical abundance per 10cc of station PL3 in 2003* and 2012

Year	#/10cc	Species richness	Margalef	Pielou's Evenness	*A. tepida*	*Bolivina* spp.	*Q. bosciana*	*A. mariae*	*E. scaber*
January									
2003	73.4	21	4.7	0.63	29.3	0.4	0.4	1.7	6.1
2012	40±11	30±2	7.1±0.1	0.89±0.01	3.5±1.7	4.5±0.3	2.6±1	3.3±0.7	3.8±0
May									
2003	18.7	8	2.4	0.61	10.9	1.3	0	0.4	0.4
2012	9.7±6	11±5	4.5±0.9	0.9±0.01	0.6±0.7	0.9±1.6	0	2.2±2.1	1.4±0
July									
2003	11.8	5	1.62	0.63	7.8	0.9	0	0	0
2012	5.3±2	8±4	4.1±0.6	0.97±0.01	0.3±0.5	1.9±0.8	0.2±0.3	0	0.5±0.5
November									
2003	0	0	0	0	0	0	0	0	0
2012	4.3±3	6±4	2.6±0.8	0.97±0.04	0.2±0.3	0.5±0.5	0	0	0.9±0.5

*** 2003 data was taken from Hyams (2006)**

Table 4.3.2: Statistical analysis of similarities (ANOSIM) using Bray-Curtis similarity. Relative abundance of each species including all samples consist >20 live specimens (replicate samples were pooled) at station PL3 and PL29 between sampling years.

	PL3		PL29	
	R	P value	R	P value
Difference between seasons	0.694	<0.05	0.149	<0.01
Difference between years (2003 vs. 2012)	0.963	<0.05	1	<0.05

Table 4.3.3: Top cm diversity indices and most dominant species numerical abundance per 10cc of station PL29 in 2003* and 2012

	Year	#/10cc	Species richness	Margalef	Pielou's Evenness	*A. tepida*	*Bolivina* spp.	*Q. bosciana*	*A. mariae*	*E. scaber*
January	2003	301.3	56	9.6	0.71	96.1	22.3	10.9	5.2	13.1
	2012	67.6±19	34±0	9.6±1.8	0.75±0.01	20±3.7	14.4±4.3	4.5±2.3	0.7±0.3	4.9±1
May	2003	251.1	50	8.9	0.74	45.4	23.6	3.1	46.3	6.1
	2012	62.4±28	35±10	9.5±1.1	0.84±0.03	7.8±2.3	13.9±11	2.8±2.7	5.2±0	2.4±0.7
July	2003	1211.8	57	7.9	0.52	607.4	50.2	30.1	145.9	55
	2012	125.5±96	41±8	10±0.7	0.8±0.06	28.7±22.6	29.2±31.3	11.3±10	4.2±2.7	6.1±3.3
November	2003	1258.5	59	8.1	0.62	379	104.8	69	46.3	169
	2012	163±63	48±11	9.9±1.8	0.8±0.04	21.4±1	17±9.3	16.2±2.3	4.7±0	21.4±9.7

* **2003 data was taken from Hyams (2006)**

Table 4.3.4: Comparison between most dominant *Bolivina* species (*B. seminude* and *B. striatula*) summed over the top 5 cm.

	PL3		PL29	
	2003	2012	2003	2012
Bolivina spp./10cc	0.51	0.84±0.42	14.19	11.68±3.16
B. seminuda (%)	37.1%	0.9±1.9%	69.2%	9.3±6.7%
B. striatula (%)	0.0%	45±13.5%	1.7%	56.1±8.7%
Other (%)	62.9%	54±14.2%	29.1%	34.6±13.4%

4.4. The dead assemblages

The Israeli continental shelf is characterized by a relatively rapid sedimentation rate of 2.3±0.5 mm/year (Almogi-Labin et al., 2009), therefore the top 2 cm tested in the current study would then represent ~10 years of accumulation, an extremely recent assemblage of dead foraminifera.

4.4.1. Dead benthic foraminiferal assemblage characteristics

The foraminiferal numerical abundance and species richness were consistently lower at PL3 compared to PL29 and PL64 for all sampling seasons (Table 3.3.1, Figure 3.3.1). This reduction in numerical abundance at the polluted site was inevitable, because it is derived from the reduced living community that decreased drastically in the past 25 years. Moreover, this difference between PL29 and PL3 could be more pronounced as a result of additional post-mortem influences such as dissolution or bioerosion (Martin, 1999).

In general the seasonal variation in both species richness and numerical abundance were very low at all stations, except for summer at station PL3 that had twice as many individuals compared to the rest of the year (Figure 3.3.1). This fluctuation was unexpected, since the top few cm (to 1 meter) commonly behave as a mixed layer controlled by turnover rate, bioturbation and sedimentation rate (Martin, 1999) with erasure of seasonal and annual signals, part of "time averaging". The amount of erasure depends on the thickness of the mixed layer and the sedimentation rate (Martin, 1999). Major nutrient input (e.g. rivers, delta or sewage outfall) might result in a periodically high sedimentation rate and more pronounced seasonality in the empty tests accumulating on the sediment. The increased numerical abundance of dead foraminifera during summer can be interpreted as a result of blooming in response to nutrient input and high organic flux (reflected in Chl *a*-sediment and TOC maxima; Figures 3.1.5d, 3.1.7) that was missed in the living community because of participation of opportunistic species with high turnover rate and high mortality in the dead assemblage. The higher sedimentation rate near the Shafdan outfall augmented by sewage sludge input helped in capturing this blooming event.

4.4.2. Assemblage composition of dead benthic foraminifera

Studies of dead foraminiferal assemblages near zones of high organic input in shallow water showed an increase in agglutinated foraminifera near the source, corroborated by studies of increased abundance of non-calcareous foraminifera in response to higher organic content (Zalesny, 1959; Watkins, 1961; Alve, 1991; Loubere & Fariduddin, 1999). Yanko et al. (1999) suggested that high occurrence of agglutinated species in the dead assemblage near sewage outfall, might be a post-mortem effect as a result of dissolution of carbonate tests in sulfide-rich (Fe_2S) black sediment.

In the current study, perforate calcareous (hyaline) foraminifera were the most dominant group (>70%) in the dead assemblage at all stations followed by porcelaneous (miliolid) tests, while the organically-cemented agglutinants were rarely found (Table 3.3.1). The relative portion of hyaline tests in the yearly average assemblage gradually decreased by up to 9% with distance from the outfall, replaced by miliolid species. Organic material degradation did not reach the critical point for carbonate test dissolution. In the central Red Sea, the down-core preservation of organic-cemented agglutinants was inversely correlated to TOC concentration (Edelman-Furstenberg et al., 2001). On the other hand, removal of organically-cemented agglutinants from the dead assemblage can occur as a result of bacterial or chemical decay of the organic material or in the course of predation of macrofauna (Murray, 2006).

The five most dominant species *A. parkinsoniana, A. tepida*, *P. subgranosus*, *A. beccarii* and *Adelosina* spp. occurred in high numbers in all three sampling stations representing together >70% of the total assemblage. Most of those species including *A. parkinsoniana, A. tepida* and *Porosononion granosum* (=*P. subgranosus*) dominate the Israeli shallow shelf over the past 5.5kyr (Tapiero, 2002) and in recent silty-clayey sediment of the Nilotic province of the southern Israeli shelf (Hyams-Kaphzan et al., 2008).

Among the calcareous species, *A. tepida*, the only species that was also dominant in the living community, was often suggested as a proxy to contamination (e.g. Bates & Spenser, 1979; Vilela et al., 2004; Frontalini & Coccioni , 2008; Hyams-Kaphzan et al., 2009 etc.). This species shows high abundance and opportunistic behavior in response to different kinds of pollution. Furthermore, other proxies for contamination such as test abnormality, pyrite filling and exclusively megalosphaeric forms of this species, were suggested as signals for contamination related to sewage outfall (Yanko et al., 1999).

The dominant species *A. parkinsoniana* predominates in the shallow Israeli shelf to 40m depth in high-energy sandy sediments of the Nilotic quartz-rich province (Hyams-Kaphzan et al. 2008; Avnaim-Katav et al. 2015). This species showed the most marked difference in numerical abundance between the three stations, with numerical abundance up to three times higher at PL29 and PL64 comparing to PL3 (Figure 3.3.3b), this ratio was also found in the living community but in much lower numbers (representing up to 5% at PL64). The correlation between *A. parkinsoniana* numerical abundance and organic material degradation (represented as TOC) at the three sampling stations is shown in Figure 4.4.1. The increasing TOC in the Palmachim stations (especially at PL3) was closely related to increase in heavy metal concentrations (Kress et al., 2013). Because this species is considered to be sensitive and intolerant to high heavy metal concentrations (Frontalini & Coccioni, 2008), it is hard to determine which factor had the strongest effect on the *A. parkinsoniana* population.

In general, the foraminiferal species with relatively large tests such as *A. beccarii*, *A. inflata* and *Adelosina* spp., all showed some fluctuation in their numerical abundance between sampling seasons at the polluted site (Figure 3.3.3d). *Ammonia beccarii* and *A. inflata* had higher relative abundance in the vicinity of the outfall at station PL3 (Table 3.3.2).

High frequencies of deformed tests were reported near contaminated areas by heavy metals and domestic sewage (e.g. Yanko et al., 1999; Frontalini & Coccioni, 2008). In the current study, a large proportion (>20% at station PL3) of *A. tepida*, *A. parkinsoniana* and *Bolivina* specimens had abnormal chamber shape or size, supernumerary chambers, twisted chambers arrangement or twisted coiling. Percentage of abnormality in this selected species decreased with distance from the outfall (Table 3.3.3). Large portion of deformed *A. tepida* tests (~30%) were also found at station PL3 in 2003 (Hyams, 2006). Abnormality was also found in other species (e.g. *A beccarii, A. inflata, P. subgranosus, T. earlandi, T. agglutinans* and some *Adelosina* specimens) but was less common with no difference between stations.

4.4.3. Multivariate analysis of death assemblage

Multivariate analysis showed a significant difference between the polluted station PL3 and the remote stations PL29 and PL64 with high similarity (>50%) between stations (Figure 3.4.4 and Table 3.4.2). The remote stations were similar and did not show any

differences between seasons. As for station PL3, most of the samples collected during July grouped with the remote stations cluster, while samples collected the rest of the year did not show any seasonal difference, as was also shown by the diversity parameters. Most of the dominant species were found in all of the samples, which explained the extremely high similarity between samples (>50%). It seems that the continual disturbance in the Shafdan area resulted in patchy, non-homogenized assemblage at the upper 2 cm of sediment. Therefore, it is likely that the assemblage as collected represents more a momentary "snapshot" rather than a fully time-averaged assemblage.

4.4.4. Post mortem characteristics

Bioerosion (boring) - Large foraminiferal tests, especially *Adelosina*, showed intensive boring covering the majority of the foraminiferal test, probably by predators, since >70% of bored *Adelosina* tests were found at station PL29 and >15% of all *Adelosina* tests of this station had extensive boring. High predation stress on foraminifera may be concluded from preference of some living species toward deeper in-sediment microhabitats at this station. At station PL3 *Adelosina* tests were rarely bored, and in the living assemblage the majority of specimens were found in the upper 2 cm (Figure 3.2.4, 3.2.7) suggesting low predation pressure.

Another viable explanation for the poor condition of *Adelosina* tests is postmortem dissolution of holes and tunnels in the calcareous wall by endolithic alga and fungi (Murray, 2006). Selective bio-erosion affecting miliolid tests more extensively and rapidly compared to rotaliid tests has been noted (Peebles & Lewis, 1988; Walker & Goldstein, 1999; Murray, 2006). In the shallow inner shelf of southwestern Sardinia burrowing traces of microbial epilithic–endolithic organisms were found on the foraminiferal calcareous tests near the polluted area where high concentration of heavy metals were recorded (Cherchi et al., 2009). These bioerosion traces were more extensive on porcelanous tests (Cherchi et al., 2012).

Pyrite filling – Pyrite can form under reducing conditions and presence of Fe, often in association with high organic content (Berner, 1970; Yanko et al., 1999). Pyritization of foraminiferal tests is a well-known phenomenon in both recent and fossil foraminiferal assemblages (e.g. Kihle, 1971; Sliter, 1975; Cearreta et al., 2002; Martins et al., 2005). Seiglie (1973) described living foraminifera individuals with pyrite crystals inside their test

(especially in *A. tepida*) therefore suggesting some association with sulfate reduction bacteria which used the foraminiferal test as a micro-environment. A more recent study found rod-shaped microbes (bacterium or archaeon) in pores plugs of living *Bolivina pacifica* specimens collected from oxygen-depleted environment of Santa Barbara Basin (California, USA). Those bolivinids were characterized by well-developed pores on their surface. The researchers suggested that larger pores may provide an adaptive advantage for associations with ectobionts (microbes that live on the outside of the test as oppose to endosymbionts; Bernhard et al., 2010). In the current study, a high frequency of well-developed pores was observed in specimens belonging to the genus *Bolivina*, the majority completely filled with pyrite. In general pyrite fill was restricted to small tests found mostly in empty tests of the most common perforate living species (mainly the genus *Bolivina, Fursenkoina, Hopkinsina* or *Rectuvigerina* as well as *A. tepida* and *A. parkinsoniana* species) and was rarely found in miliolid tests (usually in the species *Q. bosciana*). This taphonomic process may increase with sediment depth, ultimately filling even the largest shells. In the Norwegian Channel south of Mandal an increase in the portion of pyrite-filled tests with sediment depth was noted (Kihle, 1971). High frequencies of pyrite in foraminiferal tests was suggested as an indicator of pollution (Yanko et al., 1999); in southwestern Sardinia (Italy) increased abundance of pyrite-filled tests with increasing pollution was recorded (Cherchi et al., 2009). In the current study, the percentage of foraminiferal tests filled with pyrite was similar for all stations suggesting that pyritization was not related to sludge injection, furthermore high frequencies of pyrite filling were found in all the Israeli shallow shelf (Hyams et al. 2007) and in Holocene cores down to 7 meters below the surface (Tapiero, 2002).

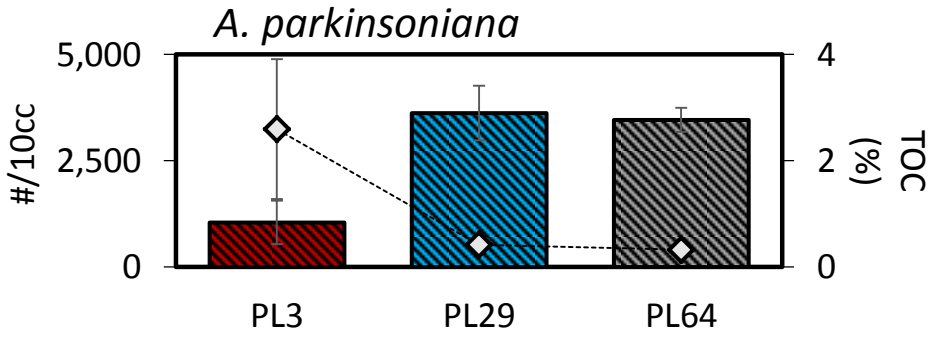


Figure 4.4.1: Top cm *Ammonia parkinsoniana* (bars; number of specimens per 10cc) vs. TOC (diamonds; wt.%) at the three sampling stations.

4.5. Comparison of Live-Dead Foraminifera Communities

Bio-monitoring is often based on living macro-benthos communities including polychaete worms and mollusks. Comparison of live-dead molluscan communities as an indication of anthropogenic influence was first introduced by Kidwell (2007). Live-dead agreement, termed "fidelity", was low in affected areas, based on depletion of residual pre-disturbance species that were joined by alien new species in the living community. Studies of foraminiferal fidelity for this purpose are rare. In this study, univariate (species richness, Margalef index, Pielou's evenness) and multivariate measures (ANOSIM test and cluster analysis) as well as methods originally developed for macro-benthos (e.g. taxonomic similarity based on percentage of joint species between assemblages) were applied to the benthic foraminiferal assemblages. Data are summarized from the upper 5 cm for the living community and top 2 cm for the dead assemblage.

The most prominent feature is that organically-cemented agglutinants, extremely abundant in the living community, representing ~25% of the assemblage at stations PL29 and PL64 and >40% at station PL3, are very poorly represented (<5%) in the dead assemblage due to degradation of the organic cement. Therefore organically-cemented agglutinants were subtracted from the living assemblages to avoid preservation bias. Level of foraminiferal live-dead agreement of species with calcareous tests were then compared to molluscan fidelity measures based on Leshno Afriat (M.Sc. thesis, 2014) which comprised a different part of the larger study of this environment.

4.5.1. Diversity index comparison

Diversity indices were calculated for both live and dead assemblages in each station (Table 4.5.1). Diversity indices at the remote stations PL29 and PL64, were similar, whereas at station PL3 the difference between the two assemblages was notable. The species richness value in the living community was low, but this low diversity was not reflected in other indices (Margalef and Pielou's Evenness) that minimalize the effect of sample size, indicating that low richness was due to the small number of remaining specimens after excluding organically-cemented agglutinants. Both Margalef index and Pielou's Evenness indicate that the differences between live and dead assemblages were higher at station PL3 than in the remote stations.

4.5.2. Assemblage composition comparison

Comparison of assemblage composition was based on the percentage of joint species between assemblages and the rank order of those species, following methods used for macrobenthic fauna (Kidwell & Bosence, 1991).

The most abundant species of the living community, with the exception of *A. tepida*, were rarely found in the dead assemblage, and vice versa (Table 3.2.2, 3.3.2 and Figure 4.5.1). The percentage of live species also found in the dead assemblage was slightly higher at station PL3 (60.1±2.4%) compared to remote stations PL29 and PL64 (53.4±7.9% and 57.7±1.8% respectively), but both are low compared to macrobenthic live-dead fidelity (85-98%) in the natural open marine environment (Kidwell & Bosence, 1991). The percentage of species in the dead assemblage found also in the living community was similar at the remote stations (52±3.2% and 47.3±2.9% respectively) but was much lower at station PL3 (24.1±9.7%), although this difference may at least be partially related to the low number of live specimens collected at station PL3. Since all dominant living species were present in the dead assemblage, the disagreement in community composition may be attributed to change in relative abundance of species.

Bolivina striatula was a highly dominant species in the living community at all stations but was rare in the dead assemblage. This species was also not common in the 2003-4 living assemblage (Hyams, 2006), so its poor showing in the dead assemblage can be explained by its recent increase in abundance. This however does not explain the numerical under-representation of all *Bolivina* (Inc. *B. striatula*), since in 2003, 2004 and 2012 they were dominant. A relatively low turnover rate of the entire genus can explain its poor representation although Edelman-Furstenberg et al. (2001) showed that in the Red Sea Oxygen Minimum Zone at ~400m depth higher relative abundance of *Bolivina* was found in the dead assemblage.

In comparison, *A. tepida* maintained a high relative abundance in both living community and dead assemblage. In 2003-4, vast numbers of small specimens (probably juveniles) were found in early spring and late summer, indicating at least two cycles of reproduction (Hyams-Kaphzan et al., 2009). Overall test representation of such an opportunistic species in the dead assemblage will therefore be higher than a species present in constant numbers that follows an annual reproductive cycle as seen in station PL3.

4.5.3. Multivariate analysis comparison

Multivariate analysis of each assemblage separately based on numerical abundance showed that samples of station PL3 clustered separately from the remote stations under 20% similarity for the living community and >50% similarity in the dead assemblage (Figures 3.4.2 and 3.4.4 respectively). In order to compare the similarity level of the assemblages between stations, another cluster analysis was conducted (Figure 4.5.2), containing the relative abundance of each species (not including organically-cemented agglutinants) of the living communities (summed over top 5 cm) and dead assemblages (summed over top 2 cm) of all samples containing >50 specimens. Under 40% similarity, two clusters of samples formed. Cluster A is composed exclusively of samples containing live specimens divided into sub-clusters (according to sampling station) while cluster B is composed strictly of dead assemblage samples from all sampling stations with some sub-divisions (>65% similarity; Figure 4.5.2). The low variation between samples in the dead assemblage that represent time averaged communities was expected. In a similar way ANOSIM test showed a significant difference between live and dead assemblages of $R=0.941$ and $P_{value} \leq 0.01$. Low live-dead agreement often relates to filtering by anthropogenic impact in the living community, with some new species entrance (Kidwell, 2013). In this study, the high difference found in the living community composition between PL3 and the remote stations is the result of anthropogenic impact. The dead assemblage had relatively high similarity between samples of different stations. Therefore, changes in the living community as a result of high organic flux have so far not been captured in the top 2 cm of dead assemblage, and a pre-impact species imprint dominates in the dead assemblage. The dead assemblage of the upper 2 cm at PL3 was not uniform, interpreted as a remnant of patchy, non-homogenized assemblage, based on multivariate measures (Table 3.4.2, Figure 3.4.4), inclusion of deeper layers would probably yield a less disturbed, better time-averaged, more homogeneous assemblage.

In general, the live-dead agreement is lower than expected compared to studies on mollusks. As foraminiferal live-dead comparison as conducted in the current study is poorly documented in the literature, it is hard to determine whether the lower live-dead agreement records anthropogenic stress also at the remote stations. In the last century the eastern Mediterranean has undergone substantial changes, mainly reflected in decreased nutrient supply and changing sediment regime related to damming of the Nile at Aswan (e.g. Inman and Jenkins, 1984; Krom et al., 1991). On the other hand, opening of

the Suez Canal allowed exotic species to migrate into the Mediterranean (Lessepsian migration; Por, 1978). Therefore the mismatch between live and dead assemblages in the control stations may have several causes besides expansion of the Shafdan plume. Possible causes can be distinguished by testing deeper sediment layers down to ~30cm to capture changes that occurred over the past 100-150 years, based on average rate of sedimentation. Comparison of dead assemblages under conditions of time-averaging will test the long-term stability of the environment, or the long-term impact of each event of environmental disturbance. A better understanding of time-averaging and the way it progresses over time beneath the surface, will also emerge.

4.5.4. Live-dead agreement compared to macrobenthic assemblages

As part of the larger study of the impact of the Shafdan input, Leshno Afriat (M.Sc. thesis, 2014) followed the seasonal change in live-dead assemblages of mollusks during 2012. She showed that live mollusks of the polluted and control stations had a similar assemblage composition, and the dead assemblage was homogenous across all seasons and sampling stations, much like that found for the foraminiferal communities. Live-dead agreement was much higher than found here for foraminifera, with constant composition of species between assemblages and high correlation coefficient of rank order of species, although univariate and multivariate data show a significant difference between live-dead assemblages. In general, although both groups (mollusks and foraminifera) consisted mainly of tolerant species, the live foraminiferal assemblage was more sensitive to organic matter input, that can be attributed to a higher turnover rate and shorter life cycle (Schönfeld et al., 2012). The significant difference between living communities of station PL3 and the remote stations is accompanied by higher live-dead fidelity in the remote stations. Similar data from the Firth of Clyde (Scotland) shows higher foraminiferal sensitivity near the disposal site of sewage sludge when living foraminifera and mollusk communities are compared. Mollusks are affected only to a distance of <3 km, while the foraminifera community is affected beyond this zone (Mojtahid et al., 2008).

Higher similarity between stations was found for dead assemblages of both faunistic groups in comparison to the living community. Foraminifera showed some variation between stations (Tables 3.3.1, 3.4.2, Figures 3.3.1, 3.4.4). Overall, there was lower live-dead agreement of the foraminiferal assemblages than shown for mollusks. However, the

sampling procedure for mollusks makes it impossible to compare data on numbers per volume (or sediment weight) for the standardized homogeneous mollusk assemblage. This highlights a major advantage of using foraminiferal data for long-term monitoring, in that beyond comparison based on relative abundance of species, numerical abundance of individual species as well as entire communities can be tracked.

The potential of foraminiferal live-dead fidelity as a sensitive indicator for anthropogenic stress is therefore shown for the Palmachim stations. Application of these findings to other natural and anthropogenically altered areas of studies of foraminiferal populations, assemblages, and live-dead fidelity based on foraminifera, will enable development of a model of expected response to level of stress, that is more sensitive than current models based on macrobiota.

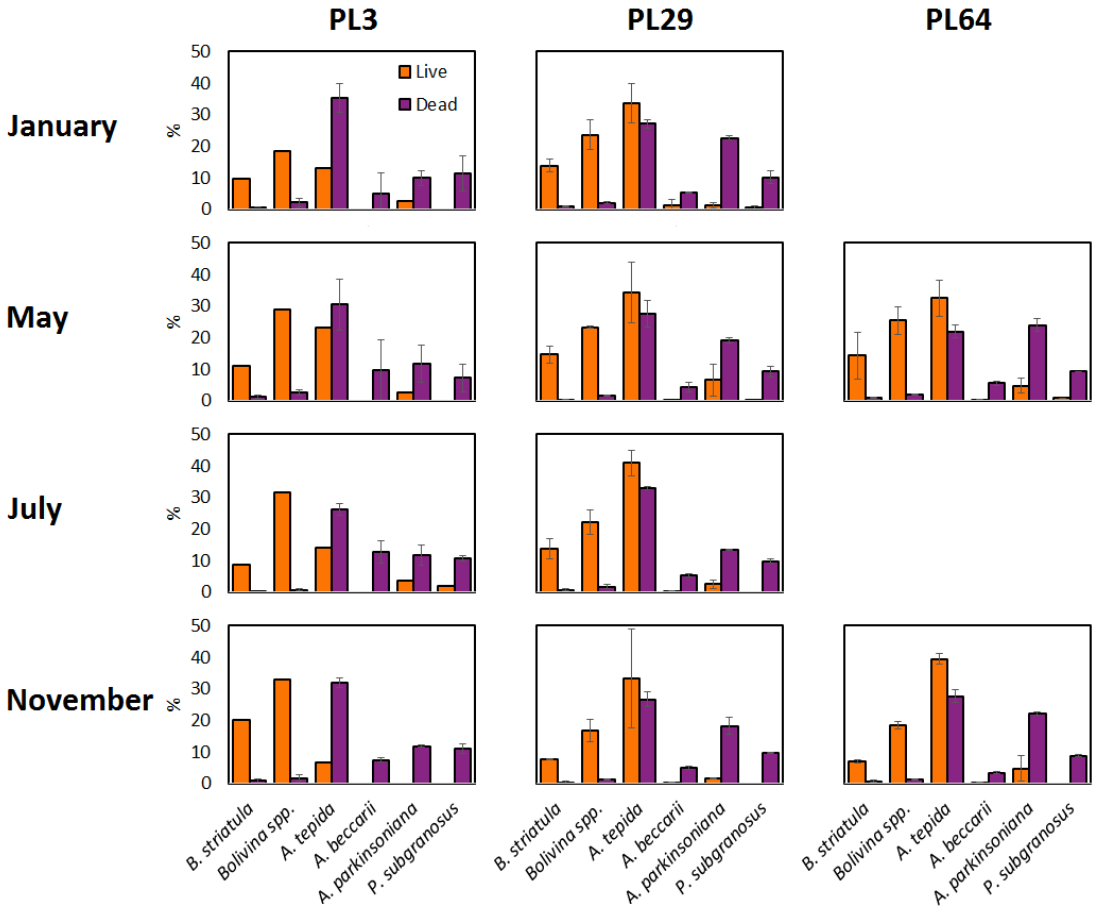


Figure 4.5.1: Relative abundance of the six most dominant taxa in all sampling stations and seasons, living community and dead assemblage summed over the top 0-5 and 0-2 cm respectively, replicate samples of the living community from station PL3 were pooled. Note *Bolivina* spp. include all *Bolivina* species, station PL64 was sampled only twice a year (May and November).

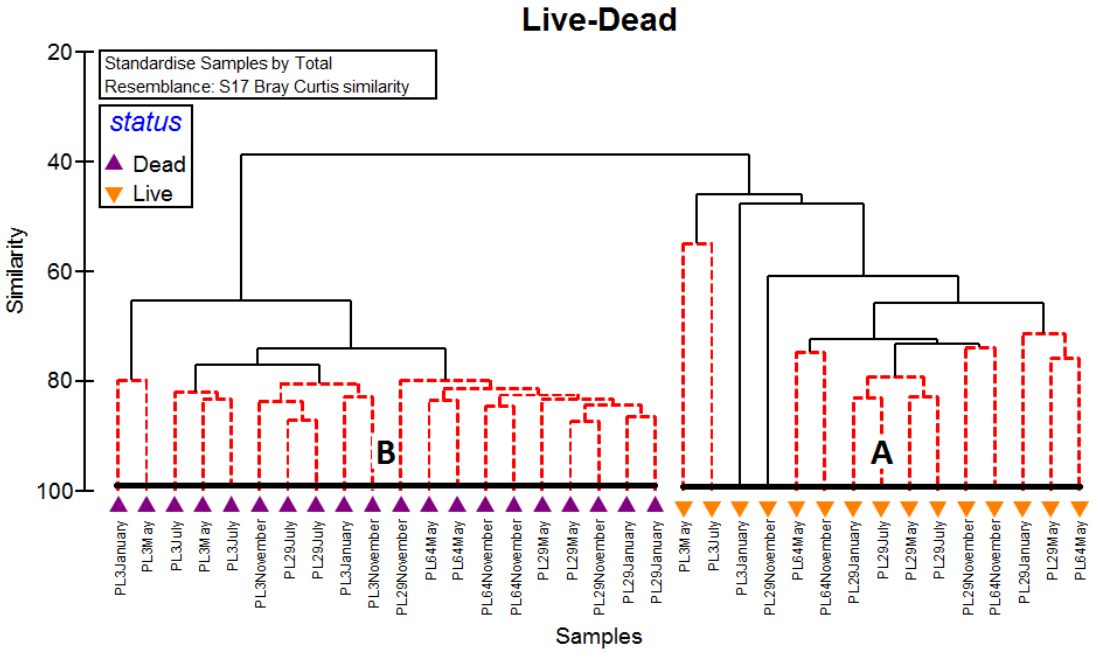


Figure 4.5.2: Dendogram classification of samples produced by Q-mode cluster analysis using Bray-Curtis similarity. Relative abundance of each species of live community summed over the top 5 cm and dead assemblage at the top 2 cm, at the three sampling stations. Only samples >50 individuals were included and organically-cemented agglutinants were excluded.

Table 4.5.1: Diversity index of total living community (top 5 cm) and dead assemblage (top 2 cm) at all sampling stations. Note organically-cemented agglutinants foraminifera were not included.

		Collected specimens	Species richness	Margalef	Pielou's Evenness
PL3	Live	297	60	11.42	0.82
	Dead	4467	112	13.45	0.61
PL29	Live	4285	110	13.39	0.6
	Dead	4685	105	12.66	0.61
PL64	Live	986	80	12.04	0.65
	Dead	2127	88	11.62	0.63

5. SUMMARY AND CONCLUSIONS

This study was aimed at tracking the long-term effect of Shafdan activated sewage sludge injection into the oligotrophic eastern Mediterranean coast using live and dead assemblages of benthic foraminifera. Changes in the living community over the past 10 years in correlation with environmental parameters, were noted so as to distinguish short-term change from enduring temporal trends. The ultimate goal was assessment of utility of live-dead benthic foraminifera assemblages as a sensitive proxy for tracking anthropogenic impact.

The database was gathered by sampling, counting and identifying living and dead foraminifera from one polluted (PL3) and two control stations (PL29 and PL64). Data was gathered at the same time on water column properties (temperature, salinity, O_2 and Chlorophyll *a*-water) and sediment properties (grain size, % dry wt. carbonate and Chlorophyll *a*-sediment). Short cores from which 5-cm cuts were taken were used for the live assemblage, while for the dead assemblage, the top 2 cm was studied, representing approximately 10 years of time-averaged test accumulation.

In comparison to the study of 2003-4, all stations experienced a decrease in TOC and Chl *a* in part due to an extremely stormy year in 2012.

At the polluted station PL3, the numerical abundance reduced in comparing to the previous study. The annual cycle begins with short-term recovery of the living community following sludge dispersal, as indicated by diversity measures, and accompanied by TOC decrease. The structure and composition of the living community then changed in the summer and fall due to accumulation of sludge, although storms were active into the spring in 2012. The dramatic decrease in foraminiferal TSS compared to 2003 is the main parameter indicating this station is still under great stress. This appears to be a strong signal of long-term deterioration that is not masked by short-term improvement.

The living assemblage was similar in both remote stations PL29 and PL64, with some seasonal and spatial variations attributed to patchy distribution mainly during the period of foraminiferal proliferation in the summer. All three stations had a dead assemblage that was similar in composition but variable in numerical abundance. At the remote stations PL29 and PL64, numerical abundance fluctuations were small, and the assemblage structure was almost homogenous due to time averaging. The fluctuation in numerical abundance in the dead assemblage in the upper 2 cm in PL3 is a strong indicator of the magnitude of disturbance caused by the Shafdan input. Those changes

shown in the living community composition that resulted from high organic flux were not captured in the top 2 cm of the dead assemblage, suggesting a pre-impact species imprint on the dead assemblage. One main finding of this study is therefore the potential of foraminiferal live-dead fidelity as a sensitive model system to predict future response to level of anthropogenic stress.

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Appendices

Sampling log book:

RT1 (Roni Tadir) - 25 January 2012

Station location:

Station	Arr.Time	Depth (m)	Latitude	Longitude
PL3	16:00	35	31º55.84'N	34º38.91'E
PL29	18:10	36.2	31º58.44'N	34º40.60'E

a. Water column

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL29	PL3
O_2, T, S, Chl-a, Turb.	CTD	5m	water	MEDEX (I. Katzman)	+	+

b. Grab – Chemistry+Foraminifera

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL3	PL29
1. Chl *a*	Directly from grabs I & II & III- 3 petri-dish; freeze, 10g	Top 0.5cm Triplicates	10g	GSI	+	+
2. TOC	Grab I / III- freeze	0-5; each cm (5 samples)	2g	GSI	+	+
3. Grain size	Grab I / III - freeze	0-5; each cm (5 samples)	3g	GSI	+	+
4. %$CaCO_3$	Grab I / III - freeze	0-5; each cm (5 samples)	0.2g	GSI	+	+
5. Living & dead foraminifera	Foram core (grabs I & II & III)-stained with RB	0-5; each cm (5 samples) Triplicates		GSI	+	+

1. At each station surface (0-0.5cm) sediment samples were taken from the first, second and third grab. At each station triplicate samples were marked I, II, III (6 samples in total).
At PL29, third grab, sediment spilled, addition sediment taken.
At PL3, third grab, the petri dish was left for ~ 5 min. before freezing.
2-4. The chemistry cores (D=5.3cm) were sliced onboard between 0-5 cm (each cm). One 100cc plastic box was sampled for chemistry analyses and another for granulometry, except PL29 one box for both analyses (frozen chemistry boxes transferred to GSI).
5. The forams cores (D=5.3cm) were sliced onboard at each cm from 0-5 cm (). At each station the 5 samples (X3 replicates) were stained with Rose Bengal (2g) mixed with ethanol (95%, 1 liter). Total- 30 samples for both stations.
At PL3 (II grab), part of the first cm was spilled, and the slice was more than one cm.
At PL3 (I grab, 4-5 cm), sample was less than 1 cm (many bivalve shells).
General remarks
The III grab at PL3 was without water from the beginning and was more clayey.
The sediment at station PL29 looked darker than at 2003, but no sludge plume was visible.
At PL3 sludge plume was visible on the water.
TOC analysis was based on dichromate method.

RT2 (Roni Tadir) - 16 May 2012 and 4 June 2012

Station location:

Station	date	Arr.Time	Depth (m)	Latitude	Longitude
PL3	16.5	12:40	35	31º55.84'N	34º38.91'E
PL29	4.6	18:00	34.3	31º58.44'N	34º40.60'E
PL64	4.6	15:56	33.3	31º59.40'N	34º41.10'E

c. Water column

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL64	PL29	PL3
O_2, T, S, Chl-a, Turb.	CTD	5m	water	MEDEX (I. Katzman)	+	+	+

d. Grab/Box corer – Chemistry+Foraminifera

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL3	PL29	PL64
1. Chl *a*	Directly from Box corer/Grab I & II & III- 3 petri-dish; freeze, 10g	Top 0.5cm Triplicates	10g	GSI	+	+	+
2. TOC	Box corer III / Grab I- freeze	0-5; each cm (5 samples)	2g	GSI	+	+	+
3. Grain size	Box corer III / Grab I/II+III – freeze	0-5; each cm (5 samples)	3g	GSI	+	+	+
4. %$CaCO_3$	Box corer III / Grab I- freeze	0-5; each cm (5 samples)	0.2g	GSI	+	+	+
5. Living & dead foraminifera	Foram core (Box corer I & II & III / Grab I & II/IV & III)- stained with RB	0-5; each cm (5 samples) triplicates		GSI	+	+	+

1. At each station a surface (0-0.5cm) sediment samples were taken from the first, second and third box corer or grab. At each station we took triplicate samples (I, II, III) (9 samples in total).

   At PL3 one of the triplicates was lost.

   2-4. The chem. cores (D=5.3cm) were sliced onboard between 0-5 cm (each cm). We sampled one 100cc plastic box for the chemistry analyses and another for granulometry analyses (frozen chemistry boxes transferred to GSI). At PL64 (Grab II) only upper 3cm taken for granulometry (too thin) , other 2cm taken from grab III.

   5. The forams cores (D=5.3cm) were sliced onboard between 0-5 cm (each cm). At each station the 5 samples (X3 replicates) were stained with Rose Bengal (2g) mixed with ethanol (95%, 1 liter). At PL3 & PL29 we sampled box corer/grab I,II,III. At PL64 we sampled grab I,III,IV. Total of 45 samples for three stations.

   General remark

   At 16/5 we sampled only PL3 using box corer because of the weather; we continued the sampling at PL29 and PL64 using grab at 4/6.

   At PL3 sludge plume was not visible on the water; it appeared later during our sampling.

   At PL3 (I box corer) was without water from the beginning and the sediment was dark gray without sludge plume.

   At PL3 (III box corer, 0-3 cm), black soft sediment with strong smell.

   At PL3 (III box corer, 4-5 cm), dark gray sediment, mainly clay.

   At PL29 the sediment was dark clay, no sludge plume was visible.

   At PL64 the sediment was bright brown sand.

RT3 (Roni Tadir) - 16 July 2012

Station location:

Station	Arr.Time	Depth (m)	Latitude	Longitude
PL3	13:20	35	31º55.84'N	34º38.91'E
PL29	15:35	35	31º58.44'N	34º40.60'E

a. Water column

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL29	PL3
O_2, T, S, Chl-a, Turb.	CTD	5m	water	MEDEX (I. Katzman)	+	+

b. Grab – Chemistry+Foraminifera

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL3	PL29
1. Chl *a*	Directly from Box corer I & II & III- 3 petri-dish; freeze, 10g	Top 0.5cm Triplicates	10g	GSI	+	+
2. TOC	Box corer I- freeze	0-5; each cm (5 samples)	2g	GSI	+	+
3. Grain size	Box corer I - freeze	0-5; each cm (5 samples)	3g	GSI	+	+
4. %$CaCO_3$	Box corer I - freeze	0-5; each cm (5 samples)	0.2g	GSI	+	+
5. Living & dead foraminifera	Foram core (Box corer I & II & III)- stained with RB	0-5; each cm (5 samples) Triplicates		GSI	+	+

1. At each station surface (0-0.5cm) sediment samples were taken from the first, second and third box corer. At each station we took triplicate samples (I, II, III) (6 samples in total).
2-4. The chem. cores (D=5.3cm) were sliced onboard between 0-5 cm (each cm). We sampled one 100cc plastic box for the chemistry analyses and another for granulometry analyses (frozen chemistry boxes transferred to GSI).
5. The forams cores (D=5.3cm) were sliced onboard between 0-5 cm (each cm). The 5 samples (X3 replicates) were stained with Rose Bengal (2g) mixed with ethanol (95%, 1 liter). Total of 30 samples.

At PL3 (I box corer, 1 cm), chemistry core slice was more than one cm.
At PL3 (II box corer), 3 cm of dark sludge.
At PL29 (I box corer, 4 cm), the sediment become denser.
At PL29 (III box corer), the first cm was disturbed but still sampled for Chl *a*.

General remark

At PL3 small sludge plume was visible: the sediment is dark.
The sediment easily mixed with Rose Bengal.
At box corer I, first cm thick sludge, 1-2 cm were liquid, 2-4 cm were filled with mollusks.
Box corer III, unhomogeneous sediment with many lumps and air pockets, the mollusk shell layer was absent, the top 1 cm was loaded with hairs.

RT4 (Roni Tadir) - 15 November 2012

Station location:

Station	date	Arr.Time	Depth (m)	Latitude	Longitude
PL3	15.11.12	11:53	37.6	31º55.84'N	34º38.91'E
PL29	15.11.12	16:40	36.1	31º58.44'N	34º40.60'E
PL64	15.11.12	18:40	36.1	31º59.40'N	34º41.10'E

c. Water column

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL29	PL3	PL64
O_2, T, S, Chl-a, Turb.	CTD	5m	Water	MEDEX (Ofer)	+	+	+

d. Grab – Chemistry+Foraminifera

Measured parameters	Procedure	Vertical resolution	Amount/ Volume	Inst.	PL3	PL29	PL64
1. Chl *a*	Directly from Box corer I & II & III- 3 petri-dish; freeze, 10g	Top 0.5cm Triplicates	10g	GSI	+	+	+
2. TOC	Box corer I at PL3 & PL29/ Box corer II at PL64 – freeze	0-5; each cm (5 samples)	2g	GSI	+	+	+
3. Grain size	Box corer I at PL3 & PL29/ Box corer II at PL64 – freeze	0-5; each cm (5 samples)	3g	GSI	+	+	+
4. %$CaCO_3$	Box corer I at PL3 & PL29/ Box corer II at PL64 – freeze	0-5; each cm (5 samples)	0.2g	GSI	+	+	+
5. Living & dead foraminifera	Foram core Box corer I & II & III- stained with RB	0-5; each cm (5 samples) Triplicates		GSI	+	+	+

2. At each station surface (0-0.5cm) sediment sample was taken from the first, second and third box corer. At each station we took triplicate samples (I, II, III) (9 samples in total).

2-4. The chemistry cores (D=5.3cm) were sliced onboard between 0-5 cm (each cm). We sampled one 100cc plastic box for the chemistry analyses and another for granulometry analyses (frozen chemistry boxes transferred to GSI). At PL29 (box corer I) only upper 4cm taken for granulometry (too thin) the last cm taken from the chemistry sample.

5. The forams cores (D=5.3cm) were sliced on board between 0-5 cm (each cm). At each station the 5 samples (X3 replicates) were stained with Rose Bengal (2g) mixed with ethanol (95%, 1 liter). At PL3, PL29 we sampled box corer I,II,III. At PL64 the third core was lost giving a total of 40 samples for 3 stations.

General remark

At PL3 large sludge plume was visible on the water about 20 m from sampling point. Dark black odoriferous sediment.

At PL3 (I box corer) 2.5 cm of sludge after the 3 cm clay sediment. Granulometry was without water.

At PL3 (III box corer) was without water. Sludge plume at 1 cm. 2-5 cm the color changed to gray brown.

At PL3 (II box corer) 2.5 cm of sludge after the 3 cm clay sediment.

At PL29 the sediment was dark brown heavy sand.

At PL29 I box core disturbed, other two better.

At PL64 the sediment was bright brown sand.

At PL3 (I box corer) was without water.

Change in crew members: Orit, Itai and Gideon were not sailing.

Plate 1. Living community -- most common species

1. *Acostata mariae* (Acosta) lateral view, k=200µm
2. *Eggerelloides scaber* (Williamson) lateral view, k=200µm
3. *Textularia earlandi* (Parker) lateral view, k=200µm
4. *Quinqueloculina bosciana* (d'Orbigny) lateral view, k=200µm
5. *Ammonia tepida* (Cushman) spiral side, k=200µm
6. *Ammonia parkinsoniana* (d'Orbigny) spiral side, k=200µm
7. *Bolivina striatula* (Cushman) lateral view, k=500µm
8. *Fursenkoina acuta* (d'Orbigny) lateral view, k=200µm



Plate 2. Dead assemblage -- most common species

1. *Adelosina dubia* (d'Orbigny) lateral view, k=500µm
2. *Adelosina intricata* (Terquem) lateral view, k=1mm
3. *Adelosina* Juvenile lateral view, k=500µm
4. *Quinqueloculina* sp. lateral view, k=500µm
5. *Ammonia beccarii* (Linnaeus) spiral side, k=500µm
6. *Ammonia beccarii* (Linnaeus) umbilical side, k=500µm
7. *Ammonia parkinsoniana* (d'Orbigny) spiral side, k=200µm
8. *Ammonia parkinsoniana* (d'Orbigny) umbilical side, k=200µm
9. *Ammonia tepida* (Cushman) spiral side, k=200µm
10. *Ammonia tepida* (Cushman) umbilical side, k=200µm
11. *Porosononion subgranosus* (Egger) lateral view, k=200µm

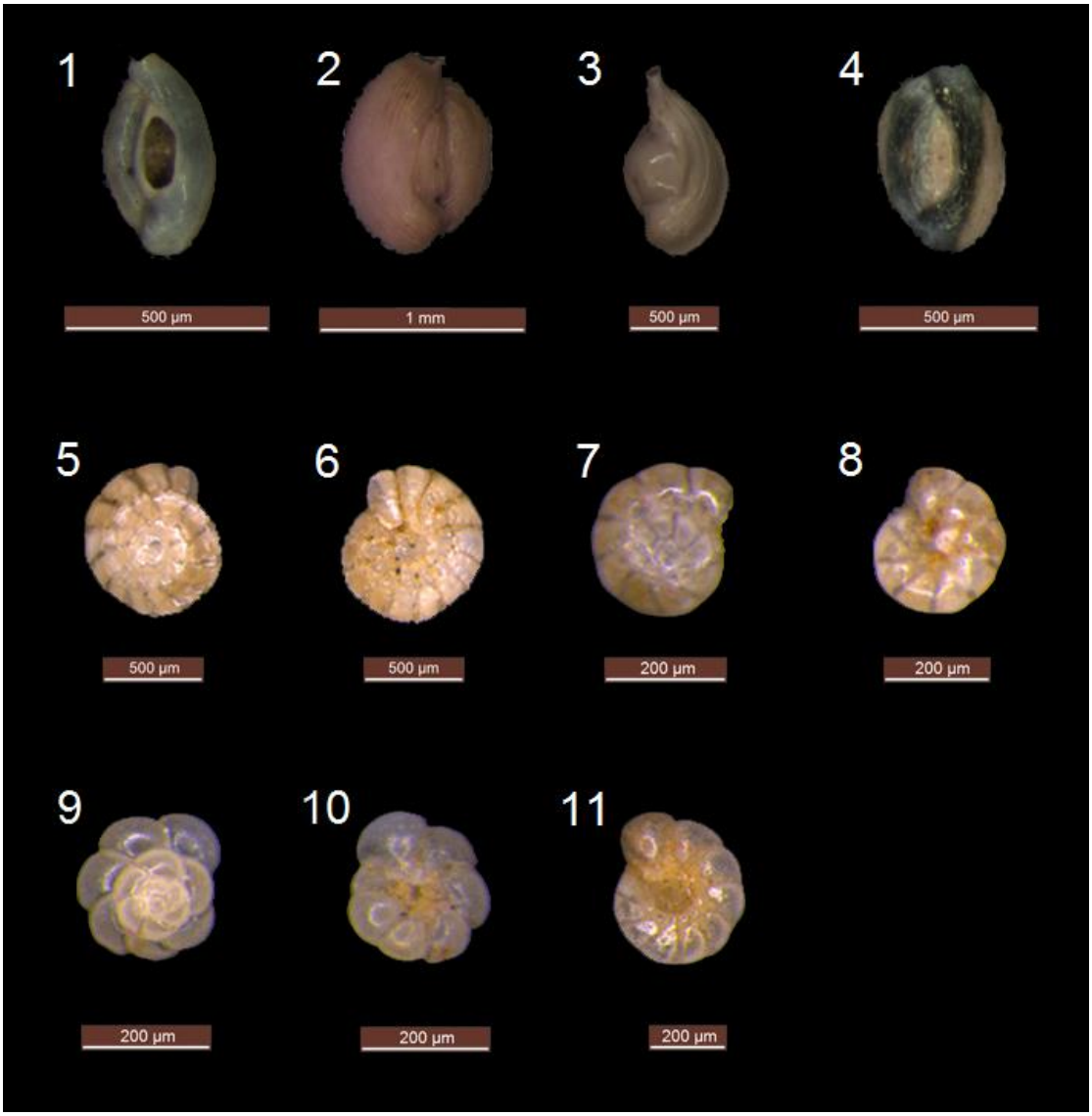


Plate 3. Mode of preservation in the dead assemblage

1-3 Examples of tests bioerosion (mainly boring) in the genus *Adelosina*

1. Extensively bored *Adelosina intricata* (Terquem) lateral view, k=500µm
2. Bored *Adelosina intricata* (Terquem) lateral view, k=500µm
3. Eroded *Adelosina* lateral view, k=1mm

4-6 Example of foraminiferal tests filled with pyrite

4. *Quinqueloculina patagonica* d'Orbigny lateral view, k=200µm
5. Miliolid unknown oblique lateral view, k=200µm
6. *Ammonia tepida* (Cushman) umbilical side, k=200µm



Foraminiferal species – absence/presence list of each assemblage

	Live			Dead		
	PL3	**PL29**	**PL64**	**PL3**	**PL29**	**PL64**
Ammonia beccarii(Linnaeus)		+	+	+	+	+
Ammonia inflata (Seguenza)	+	+	+	+	+	+
Ammonia parkinsoniana (d'Orbigny)	+	+	+	+	+	+
Ammonia tepida (Cushman)	+	+	+	+	+	+
Ammonia sp. 1	+	+	+	+	+	+
Asterigerinata mamilla (Williamson)		+	+	+	+	+
Asterigerinata mariae (Russo & Sgarrella)				+	+	
Astrononion stelligerum (d'Orbigny)		+		+	+	
Astrononion sp.		+		+	+	
Rotalinoides gaimardii (d'Orbigny)		+		+	+	+
Bolivina earlandi (Parr)	+	+	+	+		+
Bolivina seminuda (Cushman)	+	+	+			
Bolivina spathulata (Williamson)	+	+	+	+	+	+
Bolivina striatula (Cushman)	+	+	+	+	+	+
Bolivina vadescens (Cushman)		+				+
Bolivina variabilis (Williamson)	+	+	+	+		
Bolivina spp.	+	+	+	+	+	+
Buccella granulata (di Napoli Alliata)			+	+	+	+
Bulimina aculeata (d'Orbigny)	+	+	+	+	+	+
Bulimina elongata (d'Orbigny)		+	+	+	+	+
Bulimina marginata (d'Orbigny)	+	+	+	+	+	+
Bulimina sp.	+	+	+	+	+	
Buliminella elegantissima (d'Orbigny)	+	+		+	+	+
Buliminella spp.	+	+		+		
Cancris? sp.	+	+				
Cassidulina obtusa (Williamson)	+	+	+	+	+	+
Cassidulina carinata (Silvestri)		+		+	+	+
Challengerella bradyi Billman, (Hottinger & Oesterle)		+				
Cibicides advenum (d'Orbigny)					+	
Cibicides spp.				+	+	+
Cribroelphidium poeyanum (d'Orbigny)	+			+	+	+

	Live			Dead		
	PL3	**PL29**	**PL64**	**PL3**	**PL29**	**PL64**
Cribroelphidium vadescens (Cushman & Brönniman)		+	+	+	+	+
Cribroelphidium sp.	+	+	+	+	+	+
Discorbis vilardeboanus (d'Orbigny)	+	+	+	+	+	
Hanzawaia rhodiensis (Terquem)	+	+	+			
Eilohedra vitrea (Parker)	+	+	+			
Elphidium cf. *E. advenum*		+		+	+	+
Elphidium crispum (Linnaeus)	+			+	+	+
Elphidium advenum subsp. limbatum (Chapman)	+	+		+	+	+
Elphidium fabum (Fichtel & Moll)	+	+		+	+	
Elphidium sp. 3				+	+	+
Elphidium spp.		+		+	+	+
Epistominella sp.				+		
Eponides sp.					+	
Fischerinella diversa (McCulloch)				+		
Fissurina lucida (Williamson)	+	+		+		
Floresina sp.	+	+				
Fursenkoina acuta (d'Orbigny)		+	+	+	+	+
Fursenkoina complanata (Egger)		+	+	+	+	+
Fursenkoina spp.	+	+	+	+	+	
Gavelinopsis praegeri (Heron-Allen & Earland)	+	+	+		+	+
Glandulina ovula (d'Orbigny)				+		
Glabratella spp.	+			+	+	+
Globobulimina perversa (Cushman)				+		
Globulina gibba (Deshayes)		+	+	+		
Gyroidina lamarckiana (d'Orbigny)				+		
Haynesina depressula (Walker & Jacob)				+	+	+
Haynesina spp.	+	+	+	+	+	+
Hopkinsina pacifica (Cushman)	+	+	+	+	+	+
Hyalinonetrion gracillima (Seguenza)		+	+			
Islandiella sp.			+			
Lagena substriata (Williamson)	+	+		+	+	+
Lagena cf. *L. doveyensis*				+		+

	Live			Dead		
	PL3	**PL29**	**PL64**	**PL3**	**PL29**	**PL64**
Lagena spp.				+		+
Lenticulina sp.				+	+	+
Loxostomina cf. *L. africana*	+	+	+	+	+	+
Loxostomina limbata (Brady)				+		+
Nodophthalmidium antillarum (Cushman)		+	+			+
Nonion sp.	+	+		+		
Nonionella opima (Cushman)		+	+	+	+	+
Nonionella sp.		+	+			
Nonionoides grateloupii (d'Orbigny)	+	+	+	+	+	+
Nonionoides turgida (Williamson)		+	+	+	+	+
Nonionoides spp.		+		+	+	
Palliolatella fasciata (Egger)				+		
Pararotalia calcariformata (McCulloch)	+	+	+	+	+	+
Porosononion subgranosus (Egger)	+	+	+	+	+	+
Porosononion sp.					+	
Pseudononion granuloumbilicatum (Zheng)					+	
Pseudoparrella zhengae (Loeblich & Tappan)				+		
Pyramidulina catesbyi (d'Orbigny)					+	+
Rectuvigerina bononiensis (Fornasini)			+	+	+	
Rectuvigerina cylindrica (Salvatorini)		+	+	+	+	+
Reussella spinulosa (Reuss)	+	+	+	+	+	+
Reussela sp.				+		+
Reussoolina spp.					+	
Rosalina bradyi (Cushman)		+	+			
Rosalina globularis (d'Orbigny)	+	+	+	+	+	
Rosalina sp.	+	+	+		+	+
Seabrookia curta (McCulloch)				+		
Sphaerogypsina sp.	+					
Tretomphalus bulloides (d'Orbigny)	+	+	+	+		
Tretomphaloides concinnus (Brady)		+	+			
Tretomphalus sp.		+	+			
Uvigerina sp.		+				
Uvigerina?		+				

	Live			Dead		
	PL3	**PL29**	**PL64**	**PL3**	**PL29**	**PL64**
Valvulineria? bradyana (Fornasini)			+		+	
Hyaline unknown	+	+	+	+	+	+
Adelosina cliarensis (Heron-Allen & Earland)				+	+	+
Adelosina colomi (Le Calvez & Le Calvez)				+	+	+
Adelosina dubia (d'Orbigny)		+	+	+	+	+
Adelosina intricata (Terquem)				+	+	+
Adelosina longirostra (d'Orbigny)		+	+	+	+	+
Adelosina mediterrranensis (Le Calvez)				+	+	+
Adelosina milletti (Wiesner)	+	+	+	+	+	+
Adelosina spp.				+	+	+
Affinetrina sp.					+	
Agglutinella arenata (Said)		+	+			
Calocha?		+		+	+	
Cycloforina quinquecarinata (Collins)	+	+	+	+	+	+
Cycloforina spp.	+	+	+	+	+	
Lachlanella spp.		+				
Miliolinella elongata (Kruit)				+	+	+
Miliolinella subrotunda (Montagu)	+	+	+	+	+	+
Miliolinella spp.	+	+		+	+	+
Pseudolachlanella eburnea (d'Orbigny)		+		+	+	+
Pseudotriloculina laevigata (d'Orbigny)		+	+	+	+	
Pseudotriloculina sp.				+	+	
Quinqueloculina agglutinans (d'Orbigny)			+			
Quinqueloculina bosciana (d'Orbigny)	+	+	+	+	+	+
Quinqueloculina patagonica (d'Orbigny)		+	+	+	+	+
Quinqueloculina cf. *Q. parvula*				+	+	+
Quinqueloculina schlumbergeri (Wiesner)	+	+	+	+	+	+
Quinqueloculina seminula (Linnaeus)				+	+	+

	Live			Dead		
	PL3	**PL29**	**PL64**	**PL3**	**PL29**	**PL64**
Quinqueloculina viennensis (Le Calvez & Le Calvez)		+			+	
Quinqueloculina cf. *Q. compressiostoma*		+		+		
Quinqueloculina spp.	+	+	+	+	+	+
Sigmoilopsis schlumbergeri (Silvestri)	+	+	+	+	+	+
Sigmoilopsis spp.		+	+	+	+	+
Siphonaperta aspera (d'Orbigny)		+				
Siphonaperta distorqueata (Cushman)		+			+	
Siphonaperta horrida (Cushman)			+			
Pyrgoella irregularis (d'Orbigny)		+				
Siphonaperta macbeathi (Vella)			+			
Siphonaperta cf. *S. pittensis*		+				
Siphonaperta spp.	+	+	+	+	+	+
Spiroloculina spp.				+	+	
"Spirosigmoilina" sp. 1				+	+	+
"Spirosigmoilina" sp. 2			+	+	+	
Triloculina oblonga (Montagu)		+				
Triloculina marioni (Schlumberger)		+		+	+	+
Triloculina schreiberiana (d'Orbigny)		+		+	+	+
Triloculina tricarinata (d´Orbigny)	+	+	+	+	+	+
Triloculina spp.				+	+	+
Triloculinella spp.	+	+	+	+	+	+
Varidentella spp.	+		+	+		+
Wiesnerella auriculata (Egger)		+				
miliolid unknowne		+	+	+	+	+
miliolid Agglutinant		+		+	+	+
Acostata mariae (Acosta)	+	+	+	+	+	+
Adercotryma glomerata (Brady)	+	+	+	+	+	+
Ammoscalaria pseudospiralis (Williamson)		+			+	
Ammodiscus planorbis (Höglund)		+	+			+
Ammodiscus gullmarensis (Höglund)		+				

	Live			Dead		
	PL3	**PL29**	**PL64**	**PL3**	**PL29**	**PL64**
Bigenerina nodosaria (d'Orbigny)		+				
Caronia silvestrii (Brönnimann, Whittaker & Zaninetti)	+	+	+	+	+	+
Deuterammina rotaliformis (Heron-Allen & Earland)		+				
Verneuilinulla advena (Cushman)	+	+	+	+	+	+
Eggerelloides scaber (Williamson)	+	+	+	+	+	+
Haplophragmoides spp.		+				
Cribrostomoides kosterensis (Höglund)		+			+	+
Lagenammina atlantica (Cushman)		+	+		+	
Reophax fusiformis (Williamson)		+				+
Paratrochammina spp.	+	+	+	+	+	+
Pseudobolivina sp.		+	+			
Prolixoplecta sp.		+				
Leptohalysis scotti (Chaster)	+	+	+			
Reophax sp.	+	+	+		+	
Textularia earlandi (Parker)	+	+	+	+	+	+
Spiroplectammina sp.		+	+	+		+
Spirotextularia fistulosa (Brady)		+				
Textularia agglutinans (d'Orbigny)	+	+	+	+	+	+
Sahulia conica (d'Orbigny)	+	+	+	+	+	
Textularia truncata (Höglund)		+	+	+		
Textularia sp.	+	+				+
Trochammina sp.		+		+		
Agglutinated foraminifera	+	+	+	+	+	+

תקציר

אגן הלבנט בים התיכון המזרחי מוגדר כאולטרה אוליגוטרופי כתוצאה מירידה בשטף הנוטריינטים מאז סכירת הנילוס. ב-30 השנים האחרונות מאז הקמת מפעל השפד"ן בוצה משופעלת מוזרמת לים כ-5 ק"מ מערבית לחופי פלמחים, דבר המביא להעשרה בחומר אורגני ולהיווצרות גרדיינט פוריות מקומי. מחקר מוקדם שנעשה באזור בין השנים 2003-4 עקב אחר שינויים עונתיים במאסף הפורמיניפרים החיים, במהלכו נמצא שפורמניפרים רגישים לשינויים סביבתיים ומגיבים לתוספת החומר האורגני ולהצטברות בוצה על הקרקעית. בעבודה זו נבדקה רמת ההתאמה בין מאספים חיים ומתים כעשור מאוחר יותר ונבחנה השפעת עומס הבוצה לטווח הרחוק על מנת לקבל תמונה רחבה יותר שאינה מושפעת מאירועים נקודתיים. לשם כך, נבחרו שלוש תחנות דיגום במרחקים שונים משפך הבוצה: PL3 מוגדרת כמזוהמת וממוקמת בסמוך לשפך, PL29 שנחשדה בעבר כתחנה מועשרת ממוקמת 5.5 ק"מ צפונית לשפך ו-PL64 כתחנת ביקורת נקיה 7 ק"מ צפונית לשפך. במהלך שנת 2012 התבצעו 4 דיגומים בהתאם לעונות השנה (ינואר, מאי, יולי ונובמבר). דיגומים אלו כללו מעקב אחר משתנים סביבתיים: פרופיל עמודת המים (טמפ', מליחות, אחוז חמצן מומס וכו') ואיכות הסדימנט (גודל גרגר, ריכוז TOC וכלורופיל *a*), בנוסף מכל תחנה נלקחו גלעיני סדימנט לבדיקת נוכחות של פורמניפרים חיים ומתים. סך הכל נבדקו 120 דוגמאות עבור המאסף החי ו-40 דוגמאות עבור המאסף המת.

בהשוואה ל-2003-4 שנת הדיגום 2012 התאפיינה בסערות רבות, שהביאו לסילוק הבוצה בחורף ובאביב ומנעו את הצטברותה בקיץ ובסתיו. הדבר בא לידי ביטויי בירידה בריכוז ה-TOC והכלורופיל בסדימנט. בדומה לדיגום 2003-4 המאסף החי בתחנה PL3 היה מדולל ביחס לתחנות האחרות שנמצאו נקיות, והתנהג על פי מחזוריות שנתית הנשלטת על ידי סופות החורף שמאוררות את הסדימנט, ובכך מאפשרות את התחדשות המאסף. בכל התחנות ניכרה הטבה במאספים שבאה לידי ביטוי במדדי המגוון (עושר מינים, מדד מרגלף, עליה בשיוויונית וירידה בדומיננטיות), בעקבות הסערות התכופות שמנעו את הצטברות החומר האורגני בסדימנט. במקביל נרשמה ירידה חדה בכמות הפרטים החיים בתחנה PL3 ביחס לשנת 2003 כך שפרטים בודדים בלבד נמצאו דבר המעיד על ההפרעה המתמשכת באזור זה.

המאסף המת היה דומה בהרכבו בשלוש התחנות, יחד עם זאת בתחנה PL3 נצפו תנודות עונתיות בגודל המאסף שלא באו לידי ביטויי בתחנות המרוחקות. זוהי עדות נוספת להפרעה ארוכת הטווח בתחנה זו. בהשוואת המאספים חי-מת נמצא כי קיימת התאמה גבוהה יותר בין המאסף המת בכללותו למאסף החי מתחנות הביקורת המרוחקות לעומת המאסף מתחנה PL3, מאחר והשפעת העמסת החומר האורגני לא באה לידי ביטוי בהרכב המאסף המת בתחנה זו. ממחקר זה עולה כי קיים פוטנציאל גדול לשימוש במדד התאמה בין מאספי פורמניפרים חיים ומתים ככלי רגיש לחיזוי מידת הפרעה באזורים שנפגעו ע"י מעשה אדם.

המכון הגיאולוגי

משרד התשתיות הלאומיות
האנרגיה והמים

מאספים חיים ומתים של פורמניפרה כסמנים רגישים לשינויים מעשה ידי אדם במדף היבשת הרדוד של הים התיכון הישראלי

רוני תדיר

עבודה זו הוגשה כחיבור לקבלת תואר "מוסמך במדעי טבע" באוניברסיטת בן גוריון

העבודה נעשתה בהנחיית:

דר' אורית חיימס-קפצן, המכון הגיאולוגי.

ופרופ' חיים בנימיני, אניברסיטת בן גוריון.

דוח מס' GSI/ 06/2016

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