THE DIVERSITY AND DISPERSAL OF ESTUARINE INFAUNA IN MOOREA, FRENCH POLYNESIA

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Abstract. Studies examining benthic macrofauna of estuaries are becoming more prevalent in the scientific community but none have yet been conducted on the island of Moorea, French Polynesia. The present field study surveyed four estuaries on the island: the Papeahi, Paopao, Urufara and Vaihana Rivers. Organisms were collected and abiotic factors (including sediment type, depth, temperature, water flow, salinity, pH and dissolved oxygen) were measured to find correlations between species diversity and species abundances and the physical conditions that surround them. Abundance of taxa varied considerably among estuaries. Correlations were found between diversity and temperature and between gastropod abundance and depth/salinity. Many correlations reported in previous studies were absent; however this is most likely due to low abundances, small sample sizes and time constraints.

Key words: estuary, infauna, benthic macroinvertebrates, community assemblage, diversity

INTRODUCTION

Estuaries are unique and important natural ecosystems with significant economic values (EPA 2007). The brackish water and tidal range create an environment dividing the freshwater from the ocean, and organisms that live in these habitats are permanently subjected to stressful conditions (Rosa-Filho et al. 2004). The benthic macroinvertebrates of estuarine communities are critical components of the community, making up a substantial portion of estuarine biomass (Bailey-Brock et al. 2002). Benthic macroinvertebrates play an essential role in the food web as primary consumers (Salgado et al. 2007) and as a food source for other animals (Bailey-Brock et al. 2002). There is a pressing need to catalogue the distribution and abundance of macrobenthic species in estuaries, both as an indispensable tool for ecological studies (Martin et al. 1993) and as a compilation for comparative purposes in the future (Bailey-Brock et al. 2002).

Multiple factors may influence the diversity and dispersal of estuarine infauna. Some of these factors are abiotic and change with the physical surroundings (Kumar 2002, Ysebaert et al. 2002, Bailey Brock et al. 2002, Rosa-Filho et al. 2004). When these factors change, does the community assemblage change? This question can be analyzed by looking at different aspects of a community: the diversity, taxonomic group distribution and functional group distribution. Martin et al. (1993) and Salgado et al. (2007) grouped the species present in an estuarine community into trophic guilds, but did not investigate their relationship to abiotic factors. Analyzing dispersal and abundance of species based on their feeding guilds may give insight into the niche partitioning and limiting resources of benthic macrofauna.

The infauna in the estuaries on the island of Moorea have been little studied and I could not find any extensive published record of the macrobenthic community. The goal of this study is to describe the benthic

macrofauna species composition of 4 estuaries on Moorea and to better understand the habitat preferences and dispersal of the macrofauna in relation to multiple abiotic factors. Based on previous studies (Martin et al. 1993, Ysebaert and Herman 2002, Anderson et al. 2004, Gimenez et al. 2006), I hypothesized that sediment type would have the greatest effect of the abiotic factors in determining species distribution and diversity.

METHODS

Study Sites

Four estuaries were surveyed on the northern coast of Moorea: the Papeahi, Paopao, Urufara and Vaihana Rivers (Figure 1). The criteria for choosing the estuaries were sediment composition, length of the year the estuary was present, and location. All of the estuaries sampled were permanent, meaning that the river consistently ran all the way to the ocean. I chose estuaries as close together as possible to reduce community variability that might exist if I had sampled from all sides of the island. All of the estuaries were contained physically by constructed features, including rock walls on both sides of the rivers until they reached the bay or lagoon.

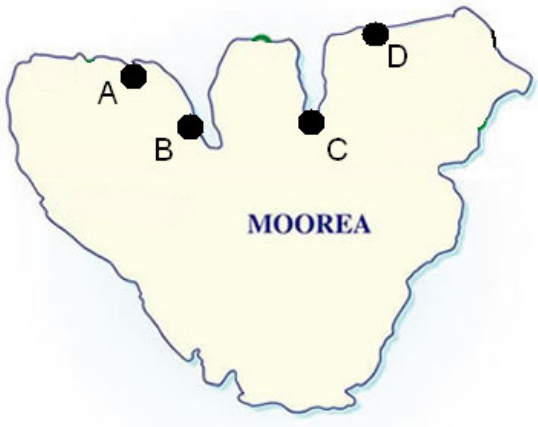

Figure 1. Sampled estuaries on the island of Moorea. A-Vaihana, B-Urufara, C-Paopao, D-Papeahi.

Biological Sampling

The goal of sampling was to obtain a representative sample of the distribution and abundance of organisms in the estuaries. The lengths of the estuaries were measured from the mouth to the end of the brackish water, determined by using a refractometer that measured salinity by parts per thousand. I positioned five line transects per estuary across the width of the channel (Figure 2). The location of each transect was determined by dividing the estuary into 4 equal segments and placing a transect at each interval. The first transect sampled was at the mouth of the estuary and the last was at the end of the brackish water. The estuaries were sampled on different days, but at each estuary, I collected all the data and samples within one day.

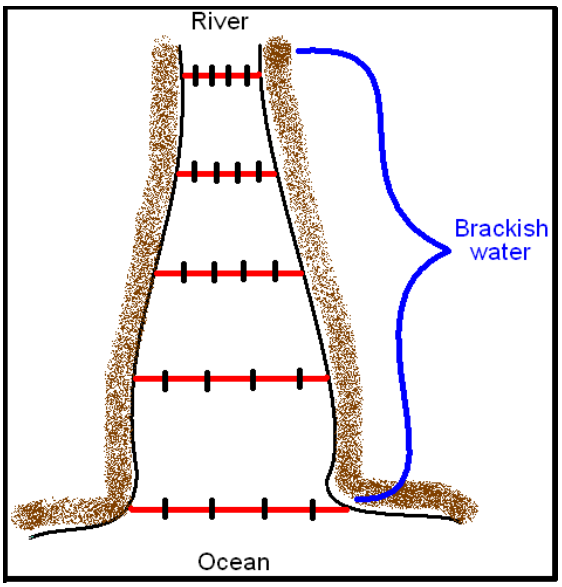

Figure 2. Bird's eye view of an estuary. Horizontal lines represent where the transects were placed. Tick marks represent where samples were taken along each transect.

It was not possible to sample at the very edge of the estuary because of the rock walls. To ensure that sample sites would not

be placed at the very edges of the estuary, four sediment cores were taken at separate, equidistant sites along each transect (Figure 2). These points were selected by dividing the length of each transect into 5 segments and sampling along the inner-intervals. The corer used was a cylinder, 15cm deep and 9.5cm in diameter. When there was solid rock at the sample site that could not be cored or collected, I collected sediment off the surface of the rock that was able to be cored. The most prevalent sediment size in each sample was recorded. The sediment size descriptions were based on categories described by the Wentworth Grain Size Scale (Leeder 1982) (Table 1). The cored sediment was sifted through 1mm mesh and the remaining sediment was transported to the lab in plastic bags. The organisms in the sediment were analyzed within 24 hours. All individuals were counted and identified to the greatest taxonomic description.

Sediment categories	Size range (mm)	Wentworth size class
Rock	64 mm and larger	Boulder Cobble
Pebble	2mm – 64mm	Pebble Granule
Sand	0.125mm – 2mm	Very coarse sand Coarse sand Medium Sand Fine sand
Silt	0.125mm and smaller	Very fine sand Coarse silt Medium silt Fine silt Very fine silt Clay
Solid Rock	N/A	N/A

Table 1. Sediment categories compared to the Wentworth size class. These are the sediment categories used in this paper and their corresponding sizes in mm and Wentworth size classifications (Leeder 1982).

Abiotic Factors

The water depth, water temperature, dissolved oxygen level, salinity and water flow were measured at each location before a sediment core was taken and as close to the sediment core as possible. Water flow was measured by releasing a fluorescent liquid, made from Fluorescin sodium salt, at the surface of the sediment and calculating the time it took to travel a measured distance. Weather conditions, sunlight exposure, containment by human action, pollution levels and other general observations and descriptions were also recorded. Water samples were collected at each sediment core location. I measured the pH of every sample and I randomly selected two water samples from each transect, one to be tested for nitrate (LaMotte Nitrate-Nitrogen testing kit) and the other for phosphate (LaMotte Phosphate testing kit, Model VM-12). I used sub-samples because I assumed that the nitrate and phosphate levels would be similar for every location across each transect.

Data Analysis

All statistical analyses were performed using JMP 7.0 (SAS Institute Inc., Cary, NC).

Principal Component Analysis (PCA)

I used Principal Component Analysis (PCA) to summarize the abiotic factors, except sediment type. I did not include the nitrate or phosphate levels in the PCA because nitrate was not present in any of the tested water samples and phosphate was present at 1ppm in only 2 samples.

The purpose of PCA is to combine my correlated abiotic variables into new, uncorrelated variables. The principal components are listed in order of how much of the variation of the data they describe (Table 5, Appendix A). PC1 describes the majority of the data, PC2 describes less, and so on. I decided to include the first 5 principal components in my statistical analyses because they represent all factors being tested. PC6 was left out because it repeats PC1.

Diversity

I computed the diversity of taxa at each location using the Shannon Diversity Index (Shannon 1948). Spirorbidae was left out of the diversity index calculations because I was not able to tell whether the organism was alive or dead. Their accumulation of calcium carbonate shells on the rocks is a misrepresentation of the living population. The first five principal components from the PCA were included in a Stepwise Fit test with diversity to find the components that significantly describe diversity. A Bivariate Fit was performed with these principal components and diversity.

The relationship between sediment type and diversity was analyzed in a One-way Anova. Because I had many more samples of rocky sediment type, I had to randomly sub-sample these points so that the number of rocky samples was closer to the rest.

Taxonomic Groups

Organisms were grouped into four taxonomic groups according to class: Gastropoda, Bivalvia, Polychaeta and Malacostraca. I used a Manova to find correlation both between the abundances of these groups and the Principal Components and between these groups and sediment type. Rocky sediment was sub-sampled.

Functional Groups

Organisms were grouped into five trophic guilds: planktivores, detrivores, herbivores, carnivores and omnivores (Table 2). I used a Manova to find correlation both between the abundances of these groups and the Principal Components and between these groups and sediment type. Rocky sediment was sub-sampled.

Species	Functional Group	Citation
Neritidae spp. A	Herbivores	Beesley et. al 1998
S. porcellana	Herbivores	Beesley et. al 1998
C. spinosa	Hrebivores	Beesley et. al 1998
N. turrita	Herbivores	Beesley et. al 1998
Diastomidae spp. A	Omnivores	Beesley et. al 1998
Diastomidae spp. B	Omnivores	Beesley et. al 1998
Cerithiidae spp. A	Herbivores	Beesley et. al 1998
Cerithiidae spp. B	Herbivores	Beesley et. al 1998
Ostreidae spp.	Planktivores	Nelson 1923
Mytilidae spp.	Planktivores	Widdows et al. 1979
Amphinomidae spp. A	Omnivores	Marsden 1963
Amphinomidae spp. B	Omnivores	Marsden 1963
Nereididae spp. A	Detrivores	Beesley et. al 2001
Nereididae spp. B	Detrivores	Beesley et. al 2001
Pisionidae spp. A	Carnivores	Beesley et. al 2001
Pisionidae spp. B	Carnivores	Beesley et. al 2001
Lacydoniidae spp.	Unknown	Beesley et. al 2001
Spionidae spp.	Detrivores	Fauchald 1979
Spirorbidae spp.	Planktivores	Fauchald 1979
Orbiniidae spp.	Detrivores	Beesley et. al 2001
Maldanidae spp.	Detrivores	Fauchald 1979
Cossuridae spp.	Detrivores	Fauchald 1979
Hemigrapsus spp.	Omnivores	Ledesma and O'Connor 2001
Paguroidea spp.	Omnivores	N/A

Table 2. Lists of species and the functional group to which they belong.

RESULTS

Taxonomic Composition

In the present study, 24 distinct taxa were differentiated and identified (Table 3, Appendix B). Out of 12,678 specimens collected (1,083 without *Spirorbidae spp.*) Annelida (50%) was the most important group in number of species, followed by Mollusca (42%) and Arthropoda (8%). Gastropoda (85%) was the dominant group in terms of abundance, exceeding Annelida (6%) and Arthropoda (4%). (All the above

calculations were computed without including *Spirorbidae spp.*).

Taxa differed between the estuaries (Table 4). The χ^2 (Chi-squared) test of independence gave a chi-squared value of 12,677.24, which is much greater than 84.82, the critical value allowed for 69 degrees of freedom. This concludes that the four estuaries are independent from each other in taxa composition.

Species	Vaihana	Paopao	Urufara	Papeahi
Neritidae spp. A	4	0	327	3
S. porcellana	256	22	149	92
C. spinosa	0	3	0	2
N. turrita	1	6	6	4
Diastomidae spp. A	0	3	0	0
Diastomidae spp. B	2	0	0	4
Cerithiidae spp. A	3	0	1	0
Cerithiidae spp. B	0	11	0	0
Ostreidae spp.	4	0	5	0
Mytilidae spp.	9	0	0	0
Amphinomidae spp. A	9	1	0	0
Amphinomidae spp. B	5	0	0	0
Nereididae spp. A	3	0	0	0
Nereididae spp. B	4	13	0	2
Pisionidae spp. A	0	0	1	0
Pisionidae spp. B	0	0	1	0
Lacydoniidae spp.	1	0	0	0
Spionidae spp.	1	0	0	0
Spirorbidae spp.	11595	0	91	0
Orbiniidae spp.	2	1	5	0
Maldanidae spp.	0	0	7	0
Cossuridae spp.	3	0	0	0
Hemigrapsus spp.	4	5	3	4
Paguroidea spp.	3	0	1	3

Table 4. A list of taxa found and the number of individuals in each estuary. (Note: Spirorbidae spp. abundances include all shells found on rocks, some of which do not contain living organisms.)

Data Analyses

Principal Component Analysis

The purpose of PCA is to combine the correlated abiotic variables into new, uncorrelated variables. Table 5 (Appendix A) shows what abiotic factors each Principal Component is dominated by. PC1 is loaded by depth and salinity. PC2 is loaded primarily by dissolved oxygen, PC3 by pH, PC4 by flow rate and PC5 by temperature. PC6 is loaded by depth and salinity, the same as PC1.

In PCA, the principal components are listed in order of how much of the variation they describe. Although PC1 describes the most of the variation (38.37%), I decided to include the first 5 principal components in my statistical analyses because they represent all factors being tested. PC6 was left out because it repeats PC1.

Diversity

The Stepwise Fit of Principal Components 1-5 and diversity showed that PC5 was the only one significant in describing diversity, with a P-value of 0.04. Principal Components 1-4 were insignificant, with P-values of 0.25, 0.60, 0.14 and 0.29, respectively. A Bivariate Fit of diversity by PC5 confirmed the Stepwise Fit with a significant P-value of 0.04 but also low overall correlation (r^2=0.05) (Figure 3). Because PC5 describes very little of the variation of the abiotic factors, we must be cautious of assuming that this is a truly significant relationship.

The One-way ANOVA of diversity and sediment type (Figure 4) showed no significance (r^2=0.06, P=0.54).

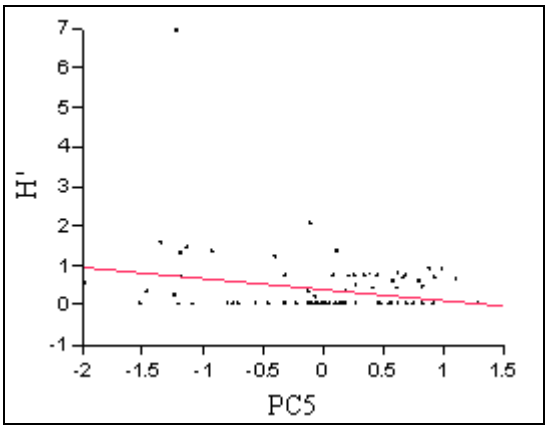

Figure 3. Bivariate Fit of Diversity (H') and Principal Component 5 (r^2=0.05, P=0.04).

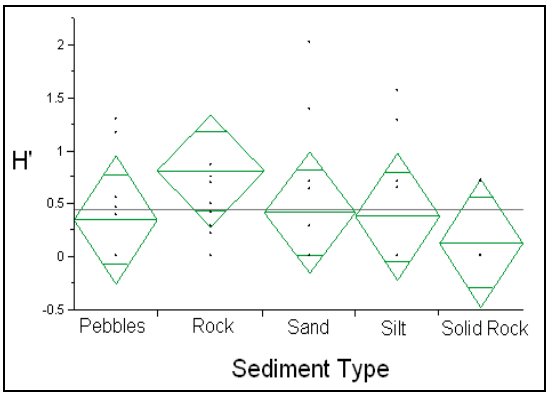

Figure 4. One-way Anova of Diversity (H') by Sediment Type. The diamonds represent the mean diversity values, none of which are significantly different from the others (r^2=0.06, P=0.54).

Taxonomic Groups

The Manova of the abundance of organisms in each taxonomic group and Principal Components 1-5 gave a Pillai's Trace Test P-vale of 0.0165 for the whole model, but the only Principal Component that showed a significant correlation (P=0.0009) was PC1. PC2 through PC5 had P-values of 0.95, 0.26, 0.32 and 0.09, respectively. A Least Squares Fit of all four functional groups by PC1 revealed that the only significant correlation was between PC1 and the abundance of Gastropoda (P=0.0002). A Bivariate Fit of Gastropoda by PC1 had a P-value of 0.0002 (Figure 5).

Manova was used to find the effect of sediment on abundance of the four different taxonomic groups. Pillai's Trace test gave a P-value of 0.5958 for the whole model, showing no significant correlation.

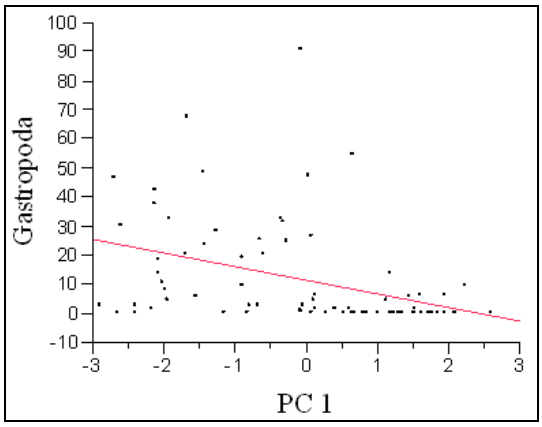

Figure 5. Bivariate Fit of Gastropoda abundances by PC1.

Functional Groups

The Manova of the abundance of organisms in each functional group and Principal Components 1-5 gave an insignificant Pillai's Trace Test P-value of 0.0913 for the whole model.

Manova was used to find significant effect of sediment on abundance of the five different functional groups. Pillai's Trace test gave a P-value of 0.1988 for the whole model, showing no significant correlation.

DISCUSSION

The diversity of taxa in the estuaries studied on Moorea is different than other estuaries that have been studied. The diversity was much lower on Moorea and taxa were found in smaller abundances. However, most estuaries in the literature cover a much larger area, are in different parts of the world and are not physically contained by rock walls like the estuaries on Moorea (Inglis and Kross 2000, Anderson et al. 2004, Rodrigues et al. 2007, Salgado et al. 2007). For this reason, I was unable compare

the taxa found in these estuaries with the estuaries on Moorea.

The patterns observed in this study differed from those expected. The results indicate an inverse relationship between diversity and Principal Component 5, which is loaded by temperature (Figure 3). However, PC5 describes very little of the variation of the abiotic factors so this may not be a truly significant correlation. The other abiotic factors had no correlation with diversity. The only taxonomic group whose abundance correlated with abiotic factors was Gastropoda. The data show that no functional groups' abundance was correlated with abiotic factors. My hypothesis was not supported because sediment type did not show significant correlation with diversity, taxonomic group abundance or functional group abundance.

The correlations that were discovered are consistent with previous studies. There are findings that temperature is correlated with faunal abundance (Kumar 2002) and that salinity and depth are main factors structuring spatial distribution (Gaudencio and Cabral 2007). Gastropod abundance decreasing with increasing depth and salinity may reflect the preferences of the certain species involved, and more research should be conducted on this subject. Many trends that previous studies have found were not significant in this study. This is most likely due to the limitations of this project, rather than the different geographical location.

A limitation of these data was the species richness and abundance of organisms found in each sediment core. Many sediment cores had one or no species, bringing the diversity to zero. With the very small range of diversity levels, it is possible that there was not enough data to be able to find correlations between diversity and the abiotic factors. There are similar problems with the taxonomic abundances and functional group abundances. Gastropoda had the largest number of individuals, and a correlation was found. If there were more individuals of every group, there may be a greater possibility of correlation. Other kinds of statistical analyses might be able to find more correlations, also.

A restriction of the sediment type analysis arose because of the unequal samples of each sediment type. I originally wanted equal samples of each sediment type. Unfortunately, a fine silt sediment estuary was unavailable so I chose to sample one that had a rockier composition. As mentioned previously, I was forced to sub-sample the rock samples in order to obtain unbiased test results. However, I believe the number of samples analyzed in each sediment type category was not sufficient to find correlations with the rest of the data.

The time constraints of this class posed a problem for this study also. I was not able to sample as many estuaries as needed. The results would be more stable if I could have sampled over a longer period of time and repeated sampling sites. Tracking the abiotic factors and sampling frequently to get averages of those values over time would provide more data to work with and solidify the findings.

Although the data did not support my hypothesis, it has fulfilled this study's goal to document the benthic microorganisms that live in estuaries on the island of Moorea. This information is now available for use in future research on these organisms or estuaries. Some species that are present in these estuaries may be used as bioassay organisms or pollution indicators (Pocklington and Wells 1992, Galope-Bacaltos and San Diego-McGlone 2002). Tracking changes in the community assemblages can tell us the health of the system. Expanding our knowledge of estuaries can keep us from destroying them in the future.

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APPENDIX A

Abiotic Factor	**PC 1**	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**
Depth (cm)	**0.561465**	0.103234	0.067213	-0.30423	0.332398	**-0.68303**
Flow rate (m/s)	0.276231	0.147168	-0.53368	**0.773228**	0.09546	-0.10116
Salinity (ppt)	**0.553269**	-0.24286	-0.11431	-0.18824	0.369721	**0.67061**
Temp (℃)	0.4934	0.356134	0.04931	-0.09726	**-0.77514**	0.130362
D.O. (mg/l)	-0.17778	**0.878742**	-0.06319	-0.16107	0.343672	0.219452
pH	0.165221	0.0984	**0.831373**	0.488593	0.157336	0.091439

Table 5. Eigenvectors from Principal Component Analysis. PC1 is loaded by depth and salinity, PC2 by dissolved oxygen, PC3 by pH, PC4 by flow rate and PC5 by temperature. These were all included in the statistical tests involving diversity, taxonomic groups and functional groups because every abiotic factor being analyzed was loaded within these principal components. PC6 is loaded by depth and salinity and was left out of the other tests because those factors were already present in PC1.

APPENDIX B

MOLLUSCA
Gastropoda
Orthogastropoda
Neritopsina
Neritoida
Neritidae
Neritidae spp. A
Neritinae
Theodoxini
Septaria
S. porcellana
Clithon
C. spinosa
Neritini
Neritina
Neritina
N. turrita
Apogastropoda
Caenogastropoda
Sorbeoconcha
Cerithiimorpha
Cerithioidea
Diastomidae
Diastomidae spp. A
Diastomidae spp. B
Cerithiidae
Cerithiidae spp. A
Cerithiidae spp. B
Bivalvia
Ostreoida
Ostreina
Ostreoidea
Ostreidae
Ostreidae spp.
Pteriomorpha
Mytiloida
Mytilacea
Mytilidae
Mytilidae spp.

ANNELIDA
Polychaeta
Palpata
Aciculata
Eunicida
Amphinomidae
Amphinomidae spp. A
Amphinomidae spp. B
Phyllodocida
Nereididae
Nereididae spp. A
Nereididae spp. B
Pisionidae
Pisionidae spp. A
Pisionidae spp. B
Lacydoniidae
Lacydoniidae spp.
Canalipalpata
Spionida
Spionidae
Spionidae spp.
Sabellida
Spirorbidae
Spirorbidae spp.
Scolecida
Orbiniidae
Orbiniidae spp.
Maldanidae
Maldanidae spp.
Cossuridae
Cossuridae spp.

ARTHROPODA
Crustacea
Malacostra
Decapoda
Pleocyemata
Brachyura
Grapsoidea
Grapsidae
Hemigrapsus
Hemigrapsus spp.
Anomura
Paguroidea
Paguroidea sp

Table 2. A list of species found in all estuaries that were sampled. Organisms that could not be identified to species are labeled as a species of the lowest taxonomic group they identified with.