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Preliminary Evaluation of the Use of Phosphogypsum for Reef Substrate in the Gulf of Mexico

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Phosphogypsum (PG), a solid by-product of phosphoric acid production in the fertilizer industry, contains radionuclides and trace metals in concentrations which are potentially hazardous to human health and to the environment. Due to the presence of these contaminants and to the lack of safe alternative uses for PG, the industry has necessarily resorted to on-site stockpiling as the primary disposal method. Thirty-three such stockpiles, totaling millions of tons of PG, are currently extant in the Gulf of Mexico region. The environmental and economic liabilities associated with PG stockpiling has prompted continuing research into alternative beneficial uses of this solid waste which will be protective of the public health. To investigate the efficacy of PG in the construction of artificial reefs, we conducted two preliminary studies which demonstrate that cement-consolidated PG may provide a suitable and safe substrate for artificial reef construction. The first, performed in the laboratory, examined the possibility of bioaccumulation of radium and six heavy metals over time when three levels (copepods, grass shrimp, and fishes) of an aquatic food chain experience both trophic and environmental exposure to PG. Other than higher radium levels in the experimental grass shrimp, little possible effect of PG exposure could be discerned. In all cases where increased metals concentrations were indicated within the experimental groups, roughly equivalent increases in metal concentrations also occurred in the control groups. The second, performed under natural conditions in four ¼-acre estuarine ponds, evaluated the effects of PG exposure on the community structures of marine meiofauna, macroinvertebrates, and fishes. Abundances of copepod species either were slightly increased in ponds with PG or were inconsistently affected. Diversity indices for macroinvertebrates and fishes showed modest but inconsistent variation among experimental and control ponds. Thus, no differences in community structure attributable to the presence of PG could be detected among benthic invertebrates, natant invertebrates, or fishes.

The fertilizer industry in the southeastern United States annually produces vast quantities of phosphogypsum (PG), a solid by-product of phosphoric acid production composed of 95% gypsum (calcium sulfate dihydrate, $CaSO_4 \cdot 2H_2O$). The constituents of the remaining 5% differentiate PG from commercially produced gypsum. While both PG and gypsum contain similar low levels of heavy metal contaminants, the metals in PG are of a purer, more crystalline (and thus more environmentally hazardous) nature. Also, gypsum contains 10 picocuries (pCi) of radium compared to 25 pCi found in PG (R. Seals, pers. comm.). Due to environmental and human health concerns caused by the presence of these contaminants, PG has been deemed unsuitable for most of the applications in which gypsum is normally applied. Lacking alternative uses for PG, industry has been limited to a single disposal method: on-site stockpiling. Within the Gulf of Mexico region, stockpiling has resulted in at least 33 PG stacks, averaging 224 acres, and has created a tremendous management problem for the industry. Environmental concerns associated with PG stockpiling, including waterborne and airborne contaminants, coupled with increasing land costs have prompted research on this solid waste for alternative beneficial uses considered protective of public health and the environment.

Any sound alternative to current PG disposal practices must address the issues of airborne radioactivity and heavy metal contact with the public, while providing evidence that PG reuse or recycling is more economical than long-term cost of both the land necessary for stockpiling and the maintenance of the stockpiles. Commercial utilization is the best long-term economic solution to reducing current and future PG inventories. Four broad categories for alternative uses of PG have been identified: 1) agriculture, 2) building construction, 3) road construction, and 4) other applications, including artificial reefs, rip rap, retaining wall backfill, coastal erosion barriers, and jetty stone. In addition to the above-mentioned coastal applications, the use of PG as an artificial substrate for oyster settlement has been suggested to complement the declining supply of natural oyster shell substrate in the Gulf region (Soniat et al., 1991; Chen et al., 1995). The utilization of PG for underwater applications provides a means for minimizing public exposure because the airborne transmission of radium (Ra), its decay products (principally radon), and various heavy metals are eliminated or significantly diminished at least. A similar logic was used in various efforts to evaluate cement-stabilized fly ash for artificial reefs on the east coast of the U.S.A. (Woodhead and Parker, 1985). Most other alternatives, while proposing economic solutions to the growing PG inventories, do not address the fundamental issue: the high potential for human exposure to PG contaminants.

A stable, abundant source of material for use in the construction of inshore artificial reefs has become imperative in many states bordering the Gulf of Mexico. Such reefs can enhance the value of both recreational and commercial fisheries by providing additional suitable habitat for a variety of invertebrates and fishes dependent on hard substrates. With Louisiana as the example, the economic significance of these fisheries can be seen. The most recent examination of the effect of recreational fishing on the Louisiana economy estimated that participants spent over $200 million (Bertrand, 1986). Additionally, the Louisiana oyster industry has been valued at over $20 million per year (Keithly and Roberts, 1988). Most of this fishing activity occurs in the shallow inshore and nearshore coastal waters. However, before large-scale use of PG in the fabrication of artificial reef materials can proceed, it must be demonstrated that PG reefs can develop healthy, diverse aquatic communities; support the growth of meiofauna, crabs, shrimp, and oysters; and enhance the populations of desirable forage and gamefish species. Furthermore, it must be shown that the potentially harmful trace element contaminants found in PG are not assimilated into the aquatic food chain and ultimately passed along to the consuming public.

To address the efficacy of using cement-consolidated PG as artificial reef material, two research efforts were undertaken. The first investigated the possibility of bioaccumulation and biomagnification of ^{226}Ra and six heavy metals through a three-level aquatic food chain. The second examined the influences of PG exposure under natural conditions on both the colonization, abundance, diversity, and distribution of meiofaunal organisms and the diversity and biomass of macroinvertebrates and fishes.

Materials and Methods

Bioaccumulation experiment.—The protocol for the bioaccumulation experiment is detailed in Nieland et al. (in press). The experimental design consisted of three components representing increasing levels of an aquatic food chain: a copepod (*Amphiascoides atopus*), grass shrimp (*Palaemonetes vulgaris* and *P. pugio*), and gulf killifish (*Fundulus grandis*). A mass culture system (System II of Sun and Fleeger, 1995) with crushed limestone and 1 kg of unconsolidated PG powder as substrate material provided PG-exposed *A. atopus* for the experiment. Control copepods were harvested from a stock of *A. atopus* maintained with limestone substrate, but without PG. The alga *Chaetoceros muelleri* was provided to both systems at a rate of ca. 10^6 cells/ml every other day.

Grass shrimp were maintained in 40-liter aquaria: three aquaria provided both a trophic exposure (PG copepods from above fed at approximately 500,000/day/aquarium) and an environmental exposure (three 5-cm diameter × 10-cm length cylindrical blocks composed of 70% PG and 30% cement) to the grass shrimp. These were stocked weekly on a rotating basis with approximately 150 grass shrimp, allowing a minimum of 2 wk and a maximum of 3 wk feeding and exposure prior to being fed to the gulf killifish. The single non-PG-exposed control aquarium was provided with three 5-cm diameter × 10-cm length cylindrical blocks composed of 70% sand and 30% cement; the grass shrimp therein were fed commercial shrimp pellets.

Gulf killifish were held in six 80-liter aquaria. Three of these were designated as experimental aquaria to which six 70:30 PG : cement blocks were added. The killifish in these were fed an average of one PG-exposed grass shrimp per fish per day. The remaining three aquaria, designated control aquaria, were supplied with six 70:30 sand : cement blocks and were provided with an average of one non-PG-exposed grass shrimp per fish per day. Control and experimental killifish were harvested for analysis at days 45, 90, and 135 of the experiment.

Samples for analysis consisted of pooled aliquots of experimental ($n = 5$) and control ($n = 4$) copepods, pooled aliquots of experimental ($n = 10$) and control ($n = 15$) grass shrimp, and the individual headless bodies of experimental (n = 14) and control (n = 26) killifish. The heads were removed from the killifish for subsequent extraction of the otoliths and microchemical analyses of same (not presented here). Each sample was digested with nitric acid for analysis of seven elements: radium (Ra), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As). Metal concentrations were measured with an inductively coupled argon plasma emissions spectroscopy (ICAP) system and were expressed as micrograms per gram wet weight. Radium analyses were conducted with the following techniques: 1) radium in the digested tissue samples was co-precipitated with a barium carrier in sulfate and 2) extracted radium was allowed to come to equilibrium with radon daughters, which then were measured by quantification of alpha particle emission in a photomultiplier. All Ra concentrations are given as picocuries per gram fresh weight.

Statistical analyses of the elemental concentration data were carried out with the GLM procedure (SAS Institute Inc., 1985) on 11 main effect means defined by species (copepod, grass shrimp, killifish), treatment (PG or control), and time of exposure (0, 45, 90, and 135 days) for killifish. In addition to analysis of variance (ANOVA) for unbalanced data, main effect means of elemental concentrations were further compared with pairwise t-tests and Duncan's multiple range tests.

Diversity experiment.—The complete protocol for the diversity experiment is described in Wilson et al. (in press). Four ¼-acre ponds (mean depth = 1 m) on the premises of the Louisiana Department of Wildlife and Fisheries' Lyle S. St. Amant Marine Laboratory were used for the study. In August 1994, two of the ponds (PG1 and PG2) were seeded with 576 cylindrical blocks of cement-consolidated PG arranged in six equidistantly spaced "reefs" (about 1 m square) of 96 blocks each (Fig. 1). The two remaining ponds [Control 1 (C1) and Control 2 (C2)] were similarly seeded with 576 cement-consolidated sand blocks. A 10-horsepower submersible pump was used to deliver 750 liters/min of ambient seawater to each pond in a flow-through manner. All four ponds were allowed to become naturally stocked with eggs and larvae of a variety of native marine organisms.

Sediment samples were collected quarterly from all ponds to quantify the abundance of meiofauna. Twelve sediment cores (2.61 cm inner diameter) were collected from each pond on each sampling date: one core taken directly

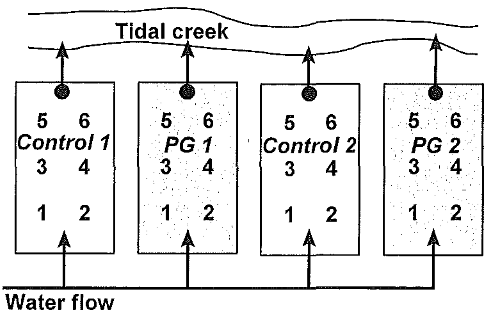

Fig. 1. Layout of control ponds (Control 1 and Control 2) and experimental ponds (PG1 and PG2) with approximate positioning of PG/cement block reefs and sand/cement block reefs (numbers 1–6).

from each of the six reefs (among) and a paired core taken equidistant from adjacent reefs (away). In the laboratory, the sediments were washed through 500- and 63-μm sieves. The material retained on the 63-μm sieve was examined, all metazoans were identified and enumerated to major taxon, and meiobenthic copepods were removed and later identified to species. A total of 192 cores were examined.

Statistical analysis of meiofauna populations was conducted by a univariate split-plot analysis of variance (ANOVA). Treatment effects associated with reef type (ponds containing PG or cement control blocks), position (cores taken among reefs or away from reefs), and collection date were examined using whole-plot analysis of the univariate split plot conducted separately on total meiofauna, abundant major taxa, and copepod species. Repeated measures multivariate analysis of variance (MANOVA) was then used to examine specific date, species, or major taxon variation as well as interactions related to the presence of PG. Species diversity was examined for the meiobenthic copepod community from samples collected among reefs with the Shannon index of diversity ($\log_e$) and Pielou's evenness index. Copepod numbers were averaged among replicates within a pond for this calculation.

At the end of 1 yr (August 1995), the ponds were drained, seined, and dipnetted to harvest the natant macrofauna of each; all blocks were also removed for assessment of oyster growth. The harvest of each pond was sorted to species, and each species lot was enumerated and weighed. The Shannon diversity index (the maximum diversity if all species are present in equal abundance), Pielou's evenness index, and the Simpson diversity were calculated for each pond (Krebs, 1972). Also, Komolgorov–Smirnov tests of goodness of fit were also ap-

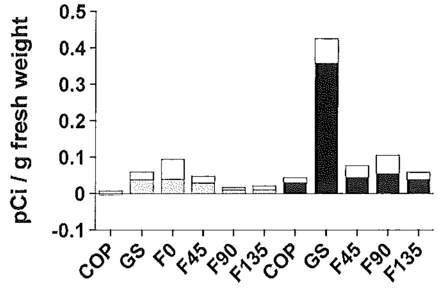

Fig. 2. Mean concentrations of ^{226}Ra for 11 categories of non-phosphogypsum-exposed (control) and phosphogypsum-exposed (experimental) organisms. Hatched bars indicate control groups and black bars indicate experimental groups. Abbreviations: COP, the copepod *Amphiascoides atopus*; GS, the grass shrimps *Palaemonetes pugio* and *P. vulgaris*; F, the gulf killifish *Fundulus grandis* (numbers following F indicate days of exposure to control and experimental conditions).

plied to both the proportions of species present and the species biomass distributions among ponds (Sokal and Rohlf, 1969). Because of the difficulty in effectively and efficiently harvesting some smaller species of fishes [gobies (Clinidae), blennies (Blenniidae), and sheepshead minnows (*Cyprinodon variegatus*)], these were only recorded as present and were not included in comparisons among ponds.

Results

Bioaccumulation experiment.—The grass shrimp that received both trophic and environmental exposure to PG were found to have a minimum sevenfold greater mean concentration of Ra than the remaining 10 groups (Fig. 2). Analysis of variance ($P < 0.05$) and both the t-test and Duncan's comparisons of means for this element suggest that bioaccumulation of Ra occurred either from the ingestion of PG-exposed copepods, from leachate of the PG blocks, or both. The Ra, a calcium analog, could have been accumulated in either the soft tissues or the exoskeleton, as has been shown in mollusks (Van der Borght, 1963; Jeffree and Simpson, 1984). However, this increase in corporal Ra concentration evidently was not passed along to the killifish. Despite slightly higher Ra concentrations among the killifish PG exposure groups, they were not found to be significantly different from those of the control killifish groups.

The analyses for Cd were complicated by the generation of many concentrations shown as zero. This does not necessarily indicate that Cd was not present; rather that it may have been present at concentrations below the level of detectability (0.001 μg/g wet weight) of the ICAP system. Among the experimental group, there is evidence of bioaccumulation of Cd from the copepods to the grass shrimp (Fig. 3). However, the increased levels of this element were not passed along as further increased concentrations to the killifish. The highest concentration of Cd found in the control copepods cannot be explained.

Apparent increases in the concentrations of Zn from copepods to grass shrimp to gulf killifish within the experimental group could be indicative of bioaccumulation (Fig. 3). However, equivalent or near-equivalent increases in Zn are shown within the control group. The concentrations shown in the copepods and grass shrimp are not significantly different from one another. Furthermore, the Zn concentrations found at all levels of exposure in both the experimental and control killifish are roughly equal to or less than the day 0 killifish. If bioaccumulation is occurring, it is occurring equally within both the control and experimental food chains. Conversely, the differences in Zn concentrations among copepods, grass shrimp, and killifish may be due to unique physiological requirements for Zn in maintaining stasis.

Among all elements surveyed, Pb showed the greatest degree of within-group variability. All mean concentrations of Pb were less than or equal to about 1 μg/g wet weight and showed little statistical variation (Fig. 3). Only the concentration of this element in killifish at 90 days PG exposure was consistently shown to be greater than the other groups. However, among 135-day killifish the concentrations of Pb are equivalent for both the control and PG-exposed groups; thus, bioaccumulation of Pb with PG as its source likely is not occurring.

Both the control and experimental grass shrimp exhibited elevated concentrations of Cu compared to the other nine groups (Fig. 3). However, this is most probably not related to any factors associated with PG exposure. A Cu-based oxygen transport molecule (hemocyanin) found in the hemolymph of grass shrimp and many other crustaceans of the subclass Malacostraca (Mangum, 1985) is thought to be largely responsible for the increased concentrations. In copepods and other small crustaceans, gas exchange is achieved by diffusion over the general body surface without the aid of an oxygen carrier (Barnes, 1974).

Concentrations of both Cr and As (Fig. 3)

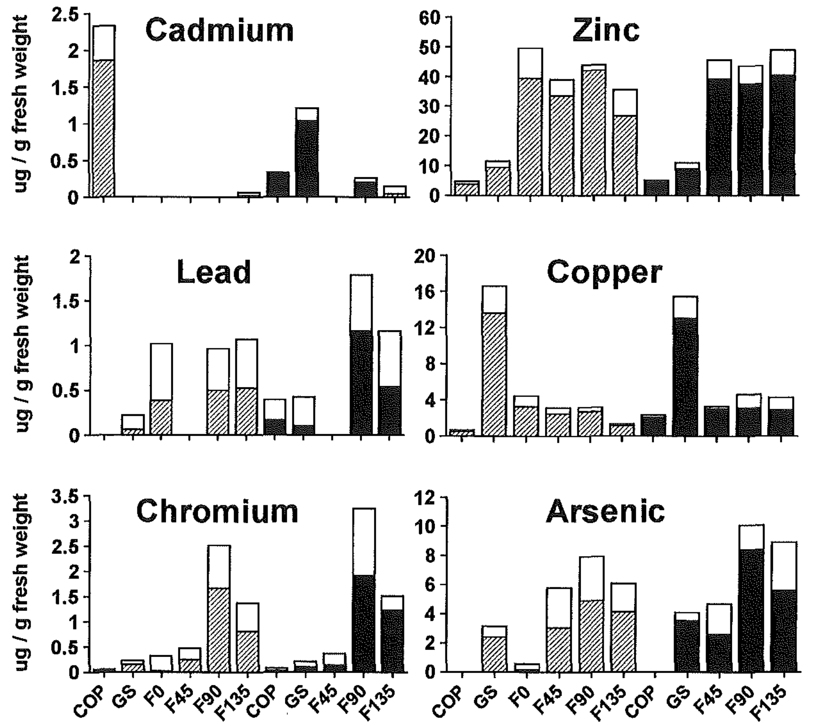

Fig. 3. Mean concentrations of six heavy metals for 11 categories of non-phosphogypsum-exposed (control) and phosphogypsum-exposed (experimental) organisms. Hatched bars indicate control groups and black bars indicate experimental groups. Abbreviations as in Figure 2.

showed a high degree of variability not only in the concentrations measured, but also in statistically significant variation. A weak argument for bioaccumulation of each could be made if one considers only the experimental data. However, largely equivalent increases in Cr and As concentrations within both the experimental and control food chains suggest sources other than PG as being responsible for increases in the concentrations of these metals.

Diversity experiment.—Total meiofauna ranged from lowest densities in December (ca. $3.7 \times 10^5/m^2$) to highest in March ($> 2 \times 10^6/m^2$) (Fig. 4). Nematodes were the most abundant taxon, averaging 83% of the total meiofauna. Trends in the seasonal abundance of nematodes mimicked that of total meiofauna. Copepods were the second most abundant taxon, comprising 7% of the total. Copepods were highest in September and March and lowest in December and June. Copepod nauplii (larval stages of benthic copepods) and ostracods were low in abundance each comprising < 10% of the total. Polychaetes (mostly juveniles) and rare taxa (e.g., tanaids and amphipods) were also found but were considered to be too low in abundance to examine statistically.

A total of 15 species (epibenthic and infaunal in lifestyle) were identified from collections. Across all collections, three copepod species comprised the majority of the meiobenthic copepod assemblage; *Cletocamptus deitersi* (Richard) and *Coullana* sp. are harpacticoid copepods and *Halicyclops coulli* Herbst is a cyclopoid copepod. During the September and December collections, *C. deitersi, Coullana* sp., and *H. coulli* composed over 85% of the copepods collected. In March and June, collections became more diverse and these three species composed only about 55% of the fauna. Two other species, *Onychocamptus mohammed* and *Paronchocamptus huntsmani,* reached high abundance only in March but were not analyzed statistically due to low numbers on other collection dates. Rare species include the harpacticoid copepods *Enhydrosoma* sp., *Harpacticus* sp., *Nitocra lacustris, Schizopera knabeni,* and unidentified species in the families Laophontidae and Ectinosomatidae.

Examination of abundance trends and the results of statistical analysis suggest that PG did

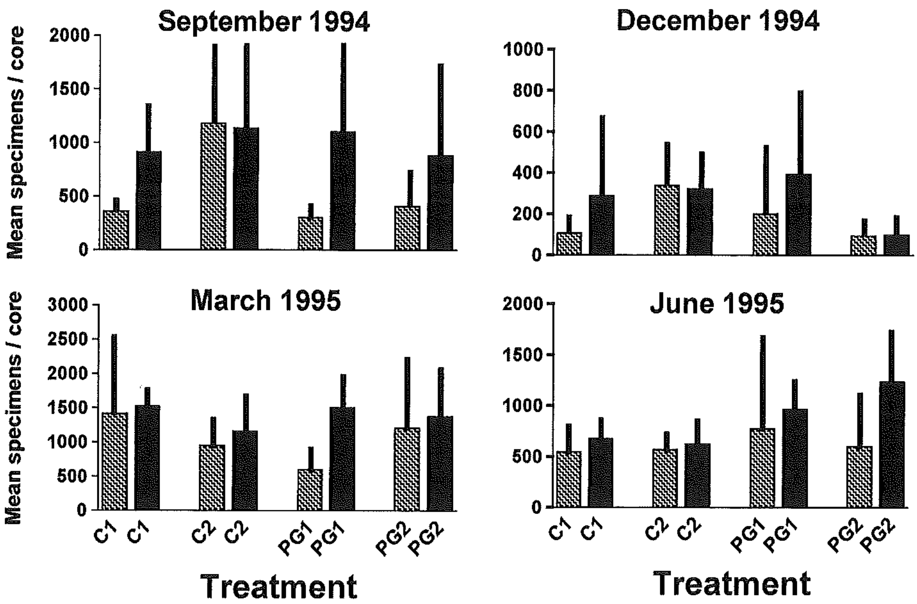

Fig. 4. Mean total meiofauna abundances per sediment core from within block reefs (black bars) and between block reefs (hatched bars). Narrow black bars indicate plus one standard error of the mean. C1 and C2 are control ponds 1 and 2; PG1 and PG2 are experimental ponds 1 and 2.

not cause consistent or long-term effects on the density of the major taxa of meiofauna. Overall, meiofaunal densities in ponds with cement (control) blocks were similar to densities in ponds containing PG blocks. Variation among replicate ponds was very high, especially in collections taken 9–12 mo after initiation of the experiment, making it more difficult to identify PG effects. Split-plot ANOVA examined PG treatment and core position effects. For total meiofauna and the major taxa of nematodes, copepods, copepod nauplii, and ostracods, no treatment effects associated with the presence of PG were found. Core position (cores taken among blocks or between blocks) was significant for all major taxa (and total meiofauna) tested, but in no instance was the PG by position interaction term significant. The lack of position by PG treatment interactions suggests that samples taken from inside the reefs were no more likely to be influenced by PG than those taken away from reefs. Generally, higher total meiofaunal and major taxon abundances were found in samples taken away from reefs. Repeated-measures MANOVA revealed that significant differences among taxa and dates occurred for all groups, but no interaction terms with PG treatment were significant.

Species diversity of meiobenthic copepods in the experimental ponds was very similar to mudflats and subtidal zones throughout south Louisiana (see Fleeger, 1985). When ponds were examined separately, species richness (measured as the number of copepod species) of collections taken among blocks ranged from three to 13, and the Shannon index ranged from 0.684 to 1.80 (Table 1). Evenness ranged

Table 1. Diversity values for the copepod assemblage as calculated by the Shannon index and Pielou's evenness index. Site designation refers to ponds C1, C2, PG1, and PG2 and to the month of collection (SE, September; DC, December; MA, March; JU, June).

Site-month	Number of species	Shannon index	Evenness
C1-SE	4	0.88	0.63
C2-SE	7	0.96	0.50
PG1-SE	6	1.13	0.63
PG2-SE	4	0.68	0.49
C1-DC	6	1.23	0.68
C2-DC	5	0.80	0.50
PG1-DC	5	1.29	0.80
PG2-DC	3	0.69	0.63
C1-MA	13	1.80	0.70
C2-MA	10	1.79	0.78
PG1-MA	9	1.71	0.78
PG2-MA	8	1.23	0.59
C1-JU	9	1.43	0.65
C2-JU	6	1.20	0.67
PG1-JU	5	1.15	0.72
PG2-JU	4	0.85	0.61

from 0.494 to 0.804. Diversity tended to be slightly higher during the spring and summer collections and slightly lower in fall and winter. Variation among replicate ponds was at least equal to, if not greater than, variation associated with treatment, and no pattern of diversity variation could be attributed to the presence of PG.

Three species of macroinvertebrates (American oyster *Crassostrea virginica,* white shrimp *Penaeus setiferus,* and blue crab *Callinectes sapidus*) and 13 species of fishes (gulf menhaden *Brevoortia patronus,* gulf killifish *Fundulus grandis,* inland silverside *Menidia beryllina,* sheepshead *Archosargus probatocephalus,* Atlantic spadefish *Chaetodipterus faber,* pinfish *Lagodon rhomboides,* silver perch *Bairdiella chrysoura,* spotted seatrout *Cynoscion nebulosus,* spot *Leiostomus xanthurus,* Atlantic croaker *Micropogonias undulatus,* black drum *Pogonias cromis,* red drum *Sciaenops ocellatus,* and striped mullet *Mugil cephalus*) were collected from the four ponds in quanitifiable numbers (Fig. 5A). Mean numbers of species (and mean biomass) found in the two experimental ponds and the two control ponds were 9.5 (32.35 kg) and 12.5 (32.41 kg), respectively. Blue crab were abundant (and quite large) in all four ponds and composed 14–30% of the numbers and 22-40% of the biomass of each (Fig. 5A). White shrimp were virtually absent from ponds C1, PG1, and PG2 but totaled 25% of the biomass and 54% of the numbers in C2 (Fig. 5A,B). Silver perch, spotted seatrout, and spot were also particularly abundant in all ponds (Fig. 5B). These three species (all members of the drum family Sciaenidae) composed 20–60% of the individuals and 21–54% of the biomass (Fig. 5A).

Diversity indices (Table 2) calculated from proportional abundances of species present showed modest variation. Indices for C1 and PG2 are virtually identical. Differences between these and the remaining two ponds appear to be driven by the numerical dominance of spotted seatrout in PG2 and of white shrimp in C2.

Komolgorov–Smirnov comparisons of the distributions of proportional species biomasses (Fig. 5A) and proportional species occurrences (Fig. 5B) among ponds revealed all four ponds to be dissimilar. Only C1 and PG2 showed similar distributions of species abundances, and all ponds showed unique distributions of biomasses among species.

Oyster growth was evident and abundant on both the PG/cement and the sand/cement blocks in all ponds; all exposed block surfaces were blanketed with a dense growth of these organisms. In many cases the oysters had formed a crown which measured 6–8 inches in diameter on the top of the blocks. Again, no manifest differences in oyster growth were noted between the experimental and control ponds.

Discussion

The two experiments reported herein demonstrated little effect of environmental or trophic exposure to PG on microinvertebrates, macroinvertebrates, or fishes which can be solely attributed to PG. No unequivocal evidence of bioaccumulation of Ra or six heavy metals could be discerned among the various trophic stages. In all cases where increased concentrations were indicated within the experimental group, roughly equivalent increases in metal concentrations also occurred in the control group. We suspect that this phenomenon is largely due to uptake from the leachate of the cement used to consolidate the sand and PG. Also, concentrations of all elements considered herein are exceedingly low and fall well below the Food and Drug Administration standards for crustaceans and bivalve mollusks used as foodstuffs (USFDA, 1996).

Our results are similar to those of Woodhead and Jacobson (1985) and Humphries et al. (1985), who evaluated the use of cement-stabilized fly ash blocks as artificial reef material. They reported rapid colonization by marine and estuarine invertebrates on both fly ash blocks and cement control blocks. Although there were differences in invertebrate communities on the two types of media, the cement-stabilized fly ash blocks were considered to be suitable for epifaunal community growth.

Meiofaunal density, taxonomic composition, and species diversity in the experimental ponds were representative of surrounding mudflats and subtidal environments (Fleeger, 1985; McCall and Fleeger, 1993). In muddy sediments, nematodes typically comprise 85–90%, and copepods 3–5%, of the total meiofauna (Coull, 1988), and the copepod species present in the experimental ponds are well studied and found in high densities throughout coastal Louisiana (Chandler and Fleeger, 1987; Sun and Fleeger, 1994; Carman et al., 1997. Densities of total meiofauna in the ponds were well within the range found in Louisiana marshes [averages 0.5–20 $\times$ $10^6/m^2$ (McCall and Fleeger, 1993)]. Previous studies in the area suggest that colonization, especially by copepods, into azoic sediment is rapid (Chandler and Fleeger, 1983; Palmer, 1988) and that den-

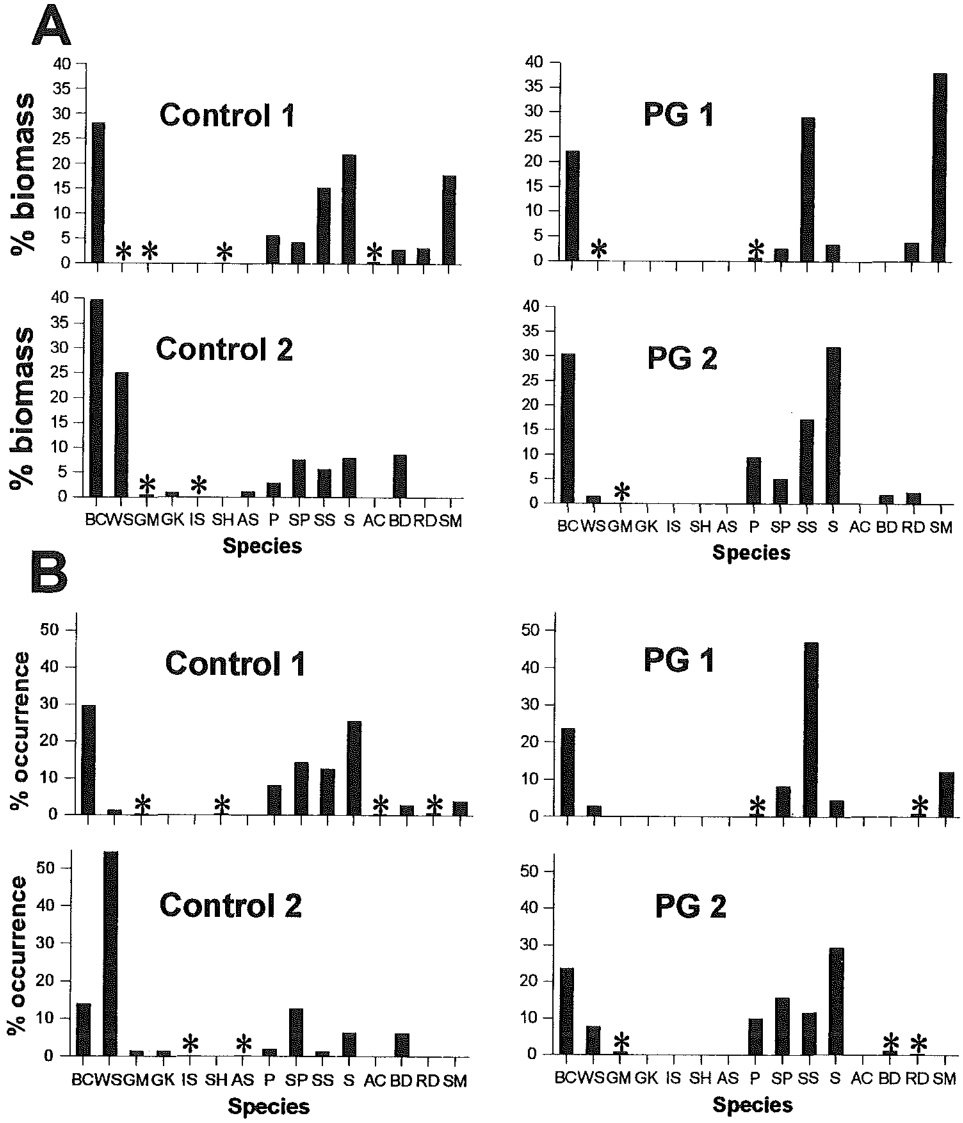

Fig. 5. Percent biomass (A) and percent occurrence (B) of two species of macroinvertebrates and 13 species of fishes in control ponds 1 and 2 and experimental ponds PG1 and PG2. Asterisks denote species present with low biomass or low numbers. Abbreviations: BC, blue crab *Callinectes sapidus*; WS, white shrimp *Penaeus setiferus*; GM, gulf menhaden *Brevoortia patronus*; GK, gulf killifish *Fundulus grandis*; IS, inland silverside *Menidia beryllina*; SH, sheepshead *Archosargus probatocephalus*; AS, Atlantic spadefish *Chaetodipterus faber*; P, pinfish *Lagodon rhomboides*; SP, silver perch *Bairdiella chrysoura*; SS, spotted seatrout *Cynoscion nebulosus*; S, spot *Leiostomus xanthurus*; AC, Atlantic croaker *Micropogonias undulatus*; BD, black drum *Pogonias cromis*; RD, red drum *Sciaenops ocellatus*; and SM, striped mullet *Mugil cephalus*.

sities in small experimental units reach background levels in 1–2 d (Sun and Fleeger, 1994). Life history traits of the abundant species (*C. deitersi*, *Coullana* sp., and *H. coulli*) favor rapid colonization through the water column (Sun and Fleeger, 1994) and high population growth rates. Thus, by our first collection 3 mo after initiation, there was sufficient time to colonize ponds and foster population growth, and densities in all ponds were high.

Phosphogypsum did not affect the density of total meiofauna or the major taxa of meiofauna. Furthermore, samples taken directly among blocks of PG were no more likely to experience effects than those taken within ponds with PG but distant from the blocks (no

TABLE 2. Diversity indices based on proportional abundances of macroinvertebrate and fish species present. Ponds C1 and C2 are controls (seeded with sand/cement blocks), ponds PG1 and PG2 are experimentals (seeded with PG/cement blocks). H, Shannon diversity, $-\Sigma\ (p_i)(\log_2 p_i)$; H_{max}, maximum diversity if all species equal in abundance, $\log_2 S$; E, Pielou's evenness index, H/H_{max}; D, Simpson diversity, $1 - \Sigma\ (p_i)^2$.

Index	C1	PG1	C2	PG2
H	2.65	2.13	2.14	2.57
H_{max}	3.58	3	3.46	3.17
E	0.74	0.71	0.62	0.81
D	0.80	0.70	0.66	0.81

position by PG by position interactions were found). Variation among replicate ponds was high, but differences in density associated with collection dates and major taxa were detectable statistically. Studies have shown that the effects of sediment contaminants are unlikely to be expressed at the level of meiofaunal phyla (Warwick, 1988), and comparisons for effects should be made at lower taxonomic levels.

The surfaces of all exposed blocks in the four ponds (reefs 5 and 6 in C1 were silted over during the course of the experiment and had only a few dead shells) supported prodigious growth of oysters. Such was their abundance that no attempt to quantify and statistically compare oyster growth and numbers among ponds and treatments was made. However, the lack of overt differences in both the quantity and the quality of oyster growth on the PG/cement and the sand/cement blocks suggests that PG provided no impediment to oyster settlement, survival, and growth.

White shrimp were found in large numbers only in C2 (Fig. 5B). The experimental ponds PG1 and PG2 and control pond C1 remained barren of flora throughout the course of the experiment. For reasons unknown to us, C2 developed a lush stand of submersed widgeon grass (*Ruppia maritima*). Pond C2 also had the smallest population of spotted seatrout (Fig. 5B), a notorious predator of shrimp. The refugia provided by the widgeon grass and the lack of predators undoubtedly combined to produce conditions favorable for the maintenance of a large population of white shrimp in C2.

Another scavenging macrocrustacean, the blue crab, would also have been expected to come in contact with the blocks and would presumably have experienced any effects of the presence of PG. Mean percent occurrences of blue crab in the two treatment groups are equivalent (Fig. 5B; 22% in control ponds, 23% in experimental ponds); however, the two control ponds did in fact show a larger overall mean percent biomass (Fig. 5A). The exceptional amount of forage and habitat provided by the widgeon grass in C2 again likely contributed to the greater biomass of blue crab found in this pond.

No clear differences in the distributions of fish species percent occurrence (Fig. 5A) or percent biomass (Fig. 5B) could be discerned among ponds or between treatments. Spot, silver perch, and spotted seatrout clearly dominated the fish faunas in all four ponds with significant contributions by striped mullet, pinfish, and black drums in C1; by striped mullet in PG2; by pinfish and black drum in C2; and by pinfish in PG2. The large number of sheepshead minnows found in C2 undoubtedly had a regulating effect on the fish population due to interspecific competition with the larval and juvenile stages of other species.

Considerations for the future.—The ultimate decision for using PG as colonizing substrate for oysters, reef material, or other aquatic applications will depend upon expansion of this line of research and an active dialogue with regulatory agencies. Assuredly, results to date warrant continuing laboratory trials and field testing of the ecological safety of PG in pursuit of this goal. Among the proposed tasks are developing an efficient procedure for the manufacture of PG composites that will maximize their strength with a minimum of effort, determining the affinity of larval marine epifauna for PG composites, investigating the suitability of small PG briquettes for settlement and growout of oysters, ascertaining the diffusion coefficients of PG leachates at different salinities, and producing a risk assessment model to predict possible long-term bioaccumulation of trace toxics through the food chain.

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