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LAGOON SEDIMENT TRANSPORT: THE SIGNIFICANT EFFECT OF *CALLIANASSA* BIOTURBATION

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ABSTRACT

Shallow backreef lagoons such as Great Pond Bay, St. Croix (U.S.V.I.) have traditionally been viewed as sediment sinks with significant transport only during storms. Recent studies in GPB show that average currents (5-15 cm/sec), coupled with intense bioturbation by *Callianassa*, result in significant down-current sediment flux and habitat modification.

Callianassa in GPB eject as much as 3.9 kg/m^2/day of sediment 5-10 cm into the water column (sandy bottom areas). This process, when superimposed on a 5-15 cm/sec mean drift, can flux 216 kg/day through a section across the central lagoon, a significant transport on a yearly time scale.

The productivity and cover of sea grasses and algae appear to be limited by *Callianassa* bioturbation.

INTRODUCTION

Backreef lagoons are generally recognized as low-energy environments in which sediment transport is minimal. Reef topography efficiently attenuates incident oceanic wave and current energy (Suhayda and Roberts 1977, Roberts, 1980); backreef circulation is primarily the product of reef overwash and tidal activity. Larger water bodies such as atoll lagoons have current regimes dominated by wind stress (von Arx 1954). With the exception of well-defined tidal passes, these shallow systems are generally characterized by weak ambient currents, incapable of moving sand-sized sediment. Sediment transport by physical processes alone appears to be significant only during storms.

Hummocky topography of lagoon floors indicates intense biologic activity. Volcano-shaped mounds reveal the presence of abundant subsurface bioturbators such as holothuroids (Rhoads and Young 1971, Suchanek, in prep.), enteropneusts, polychaetes (Suchanek, in prep.), and, most importantly, shrimp (Shinn 1968, Aller and Dodge 1974, Clifton and Hunter 1973, Suchanek, in prep.). These deposit feeders rework and sometimes resuspend sediments in temperate environments (Rhoads 1967, 1970, 1973, Rhoads and Young 1970, 1971) as well as tropical ones (Shinn 1968, Aller and Dodge 1974, Clifton and Hunter 1973). In backreef lagoons the most significant mound builder is the Thalassinid shrimp *Callianassa*. Mound densities may exceed 10/m^2, and mound heights may reach 30 cm. Sediment processed in intricate burrows is ejected 5-10 cm into the water column through an opening at the mound top. In the presence of waves and currents, these bioejections can be important sediment transport processes and have an impact on the initiation and survival of sea grass beds and algae in shallow lagoons. Data for this study of the influence of *Callianassa* bioturbation on sediment transport and habitat modification in a low-energy backreef lagoon were collected from Great Pond Bay, St. Croix, U.S. Virgin Islands (Fig. 1).

METHODS

Physical process data were collected at sites indicated on Figure 2. Wind speed and direction were continuously recorded at the instrument tower site. In situ recording current meters were placed in the tidal passes and the central part of the lagoon. Spatial variability of currents was studied by drogue tracking, dye drops, and current meter profiles throughout the lagoon.

The distribution and abundance of *Callianassa* mounds and sea grasses were determined by using a 1 m^2 quadrat with lines strung at 25-cm intervals across the quadrat, yielding 25 intersecting points. Replicate haphazard tosses were made at each of 71 stations in the lagoon (Fig. 3). The abundance of mounds/m^2 for each toss was recorded, as was the number of points lying over grass, algae, or sand. Maximum height of mounds was measured with a meter stick. Mound ejection rates and plume heights were recorded over 60-min observation intervals. Mound pumpings were collected in sediment traps secured directly over the eruption hole of

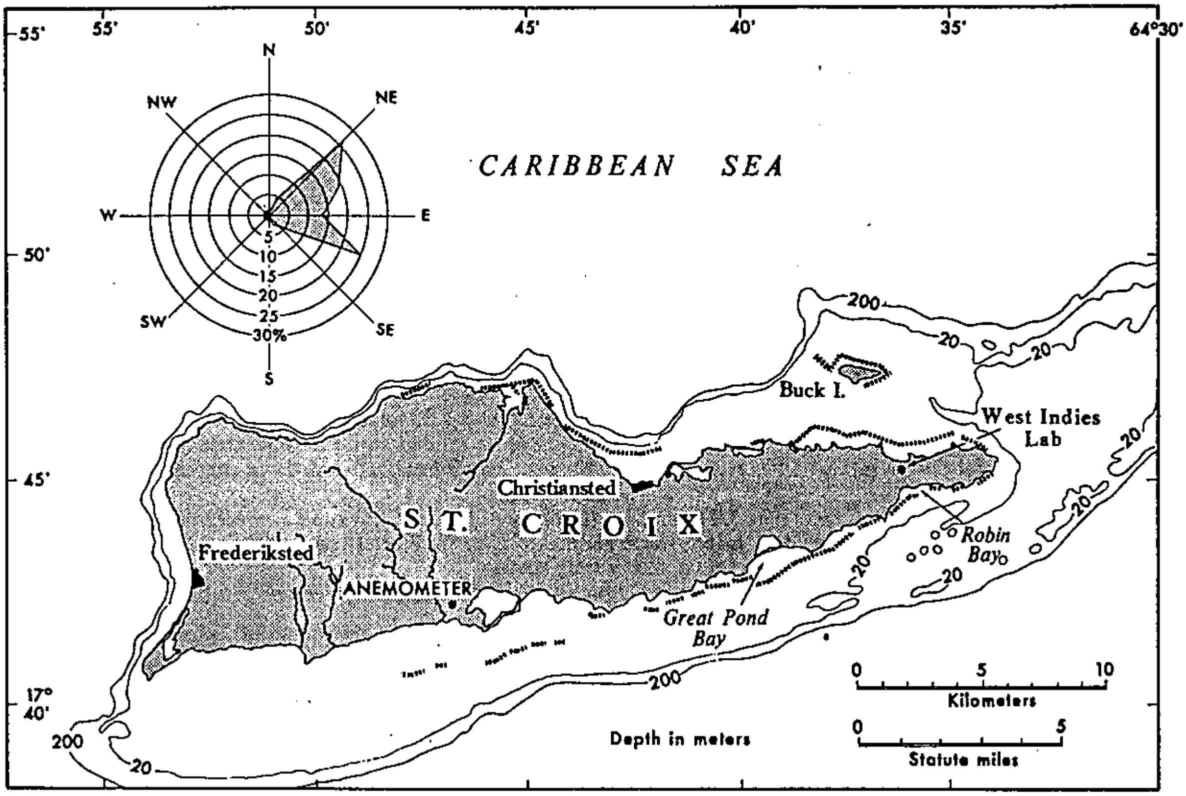

Figure 1. Index map of St. Croix, U.S. Virgin Islands, and the Great Pond Bay study site.

a flattened mound. Pumped sediments were collected in six replicate traps for 24-h periods in each of one sea grass bed and three sandy areas. Grain size analyses (Folk 1974) were performed on bioejected sediments.

TRANSPORT PROCESSES

Great Pond Bay exhibits a homogeneous water structure both vertically and horizontally. Flow within the bay is essentially westerly and modulated by the tides. A characteristic value for the current is 10 cm/sec, suggesting rapid renewal of the water within the bay. At this speed, a water parcel could traverse the 3-km length of the bay in about 8 h.

Major variations in the flow through the bay appear to correlate with major changes in the wind field and wave state. Approximately 75% of the water exiting the bay through the western pass enters across the reef crest, the remainder entering through the eastern pass. Having crossed the reef, water initially flows in a northwesterly direction under the influence of the local wind, later turning parallel to the north shore and accelerating as it approaches the western pass (Fig. 2). Drogues recorded speeds of up to 25 cm/sec within the bay. The mean speed from a continuous 2-week record, though, was only 6.3 cm/sec (Fig. 4). The flow was extremely persistent, the major variance being associated with tidal frequencies and overtides. Higher frequency variability associated with waves can attain peak speeds of 50 cm/sec (Fig. 4).

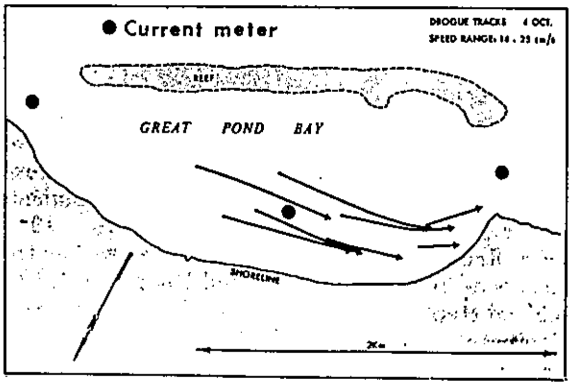

Figure 2. Basic lagoon circulation pattern established by drogue tracks and in situ current meter locations.

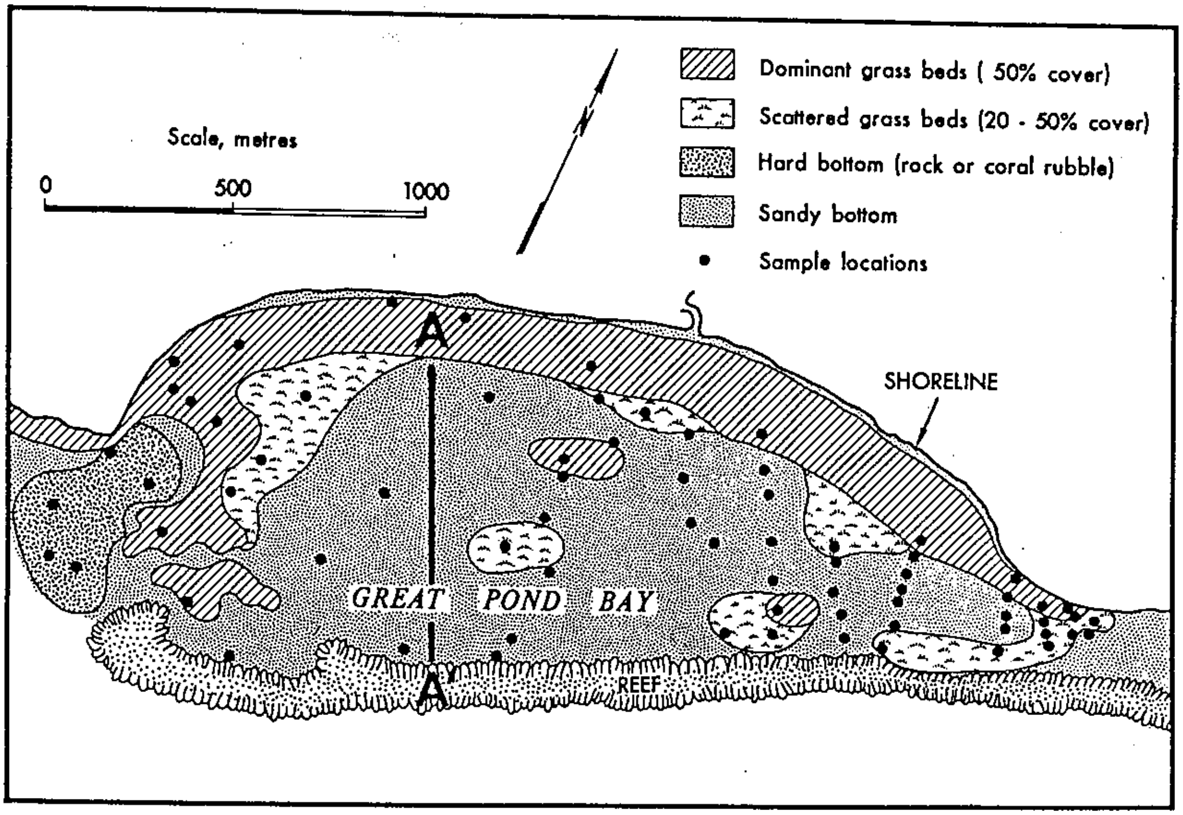

Figure 3. General substrate map of the Great Pond Bay as interpreted from observations at 71 sample stations. Digitized data indicate that dominant grass beds occupy 27%, scattered grass beds 12%, and sandy bottom 53% of the lagoon floor. Patch reefs are not shown. A-A' is the section across which sediment transport values are calculated.

We were unable to track drogues during squalls. It appears, though, that these strong short-term events may be very important to transport processes within the bay.

CALLIANASSA BIOTURBATION

The lagoon is characterized primarily by four substrate types (Fig. 3): dominant sea grass beds (> 50% cover by sea grasses), sandy bottom, patch reefs, and hard bottom (rock or coral rubble). Grass (25-30% of bay) cover consists mostly of a mixture of the grasses *Thalassia testudinum* and *Syringodium filiforme* with less abundant *Halodule wrightii* and some algae *(Dictyota* spp., *Acanthophora spicifera, Penicillus* spp. and *Halimeda* spp.). Scattered grass beds have 20-50% cover. Sandy substrates usually have high concentrations of *Callianassa* mounds. Patch reefs and hard bottom have neither grasses nor *Callianassa*.

The average abundance and height of *Callianassa* mounds from the sandy bottom are significantly greater than in the sea grass beds (Table 1). In addition, the activity rate of *Callianassa* (ejections/h), the amount of sediment pumped (per 24 h), and the height of sediment eruption plumes all show significantly greater values in sandy bottom regions than in sea grass beds. However, ejection durations appear to be relatively consistent between the two areas.

Bioejections of sediment show significantly larger mean grain sizes in the grass bed areas than in the sandy bottom (Table 1). The greatest difference in the size distributions arises from an increase in the fine component (2.5-3.0 Φ) of sandy bottom substrate ejections, a trend thought to reflect the natural sediment kurtosis encountered by *Callianassa* and not a difference in pumping behavior in the two regions. Thus considerably more sediment (3.395 kg/m^2/day) is processed in the sandy area than in the grass beds (0.819 kg/m^2/day).

In addition to contributing significantly to sediment transport, *Callianassa* (by virtue of its continual sediment processing) may also have a major effect on the distribution of sea grasses and algae. The maximum productivity and percent cover that sea grasses and algae attain appears to be limited by, or

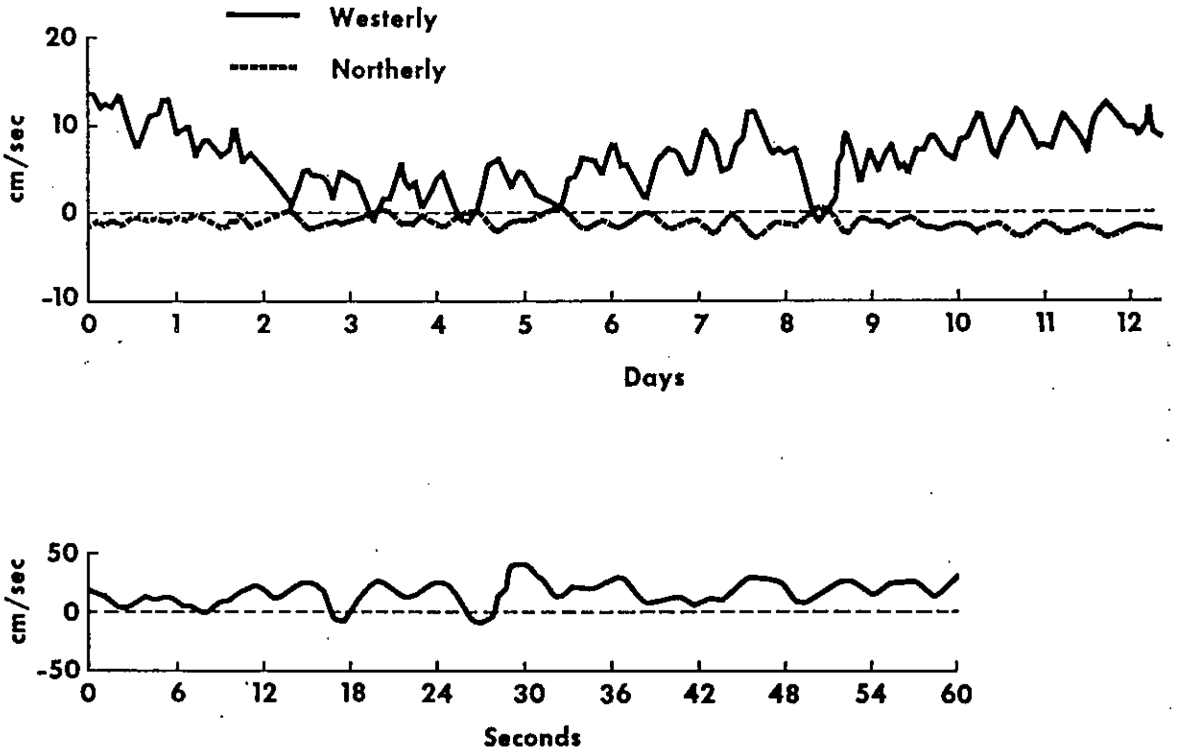

Figure 4. Time series records of currents in the central portion of Great Pond Bay. For meter location see Fig. 3. Note scale changes between records.

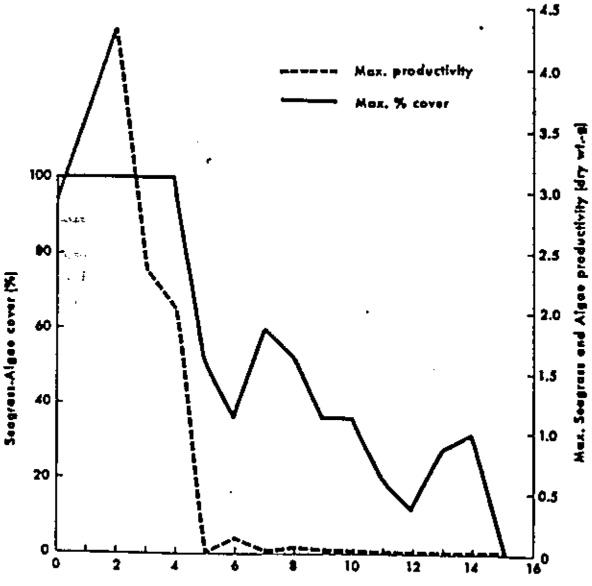

Figure 5. A summary of data showing the relationship between *Callianassa* burrowing and seagrass-algae cover as well as productivity.

at least negatively correlated with, the number of *Callianassa* mounds/m^2 (Fig. 5). Although cover can be quite variable for a moderate number of *Callianassa* mounds (5-10/m^2), productivity is drastically reduced in areas having $\geq$ five mounds/m^2.

SEDIMENT TRANSPORT

As the burrowing *Callianassa* ejects sediment, this sediment is advected downdrift by the mean flow regime while it settles from suspension (Fig. 6). To evaluate the potential importance of this mechanism, *Callianassa*-induced transport was estimated under different assumed mean flow conditions: 10 cm/sec to represent the flow 1 m off the bottom under ambient conditions, 25 cm/sec under accelerated flow conditions, as might be expected with strong prolonged wind events, and 50 cm/sec under storm conditions. These transports are compared to the expected bedload transport under the same mean flow conditions. Finally, total transport catalyzed by *Callianassa* through a cross section of the lagoon, running from the reef to the shore, was estimated. The fundamental data on which these estimates are based are presented in Table 1.

Table 1. Statistics on *Callianassa* mound density, distribution and sediment ejections for sandy bottom regions and grass beds in Great Pond Bay.

	Sandy Bottom	Grass Beds	Significance[a]
Mound density (per m²)	6.7 ± 2.4	2.1 ± 1.4	***$p < 0.001$
Mound height (cm)	13.5 ± 3.3	5.6 ± 4.0	***$p < 0.001$
Ejections/mound/hr	23.5 ± 3.5	11.0 ± 1.4	*$p < 0.05$
Dry weight sediment ejected/mound/day	508.2 ± 72.5	397.7 ± 23.5	**$p < 0.01$
Mean grain size (ϕ)	2.3 ± 0.2	1.7 ± 0.2	***$p < 0.001$
Ejection height (cm)	5.4 ± 0.7	2.5 ± 1.1	*$p < 0.05$
Ejection duration (sec)	10.5 ± 2.2	11.2 ± 1.9	ns
TOTAL SEDIMENT PROCESSED (kg/m²/day)	3.395	0.819	

[a] Significant differences between means were tested with student's t-test (Sokal and Rohlf 1969).

Over the sandy bottom substrate, sediment is ejected by *Callianassa* to an average height of 5.4 cm. Spherical particles of diameter 2.32 ϕ (Table 1) obey a viscous settling law (Inman 1963). With an effective density of 2.7 g/cm³ they require 1.3 sec to settle to the bottom. The particle shapes are not spherical, their density is probably less than assumed, and turbulence is ignored; all these factors suggest the particles actually spend longer than 1.3 sec in suspension. The assumed velocity profile near the bottom is logarithmic (Monin and Yaglom 1971),

$$u(z) = \frac{u_*}{\gamma} \ln \frac{z - z_1}{z_0} \qquad (1)$$

where u(z) is the velocity at a height z above bottom, γ is von Karman's constant (0.4), u_* is the shear velocity, z_1 is a displacement height of the order of the bottom roughness element height, and z_0, the roughness length, is approximately 1/30 of the roughness element height. The roughness element height was taken to be the mean *Callianassa* mound height. Using (1), u_* was determined for the various flow conditions. The average transport velocity (Table 2) over the 5.4-cm height of sediment

Table 2. Sediment transport results.

Conditions	Ambient	Accelerated	Storm
Current Velocity U_{100} (cm/sec)	10	25	50
Shear Velocity u_* (cm/sec)	0.75	1.87	3.74
Avg. Transport Velocity (cm/sec)	6	15	30
Transport Rates kg/m/day	0.27	0.66	1.32
Total Flux kg/day	216	528	1056
Bedload Only kg/m/day	0	0	20-30

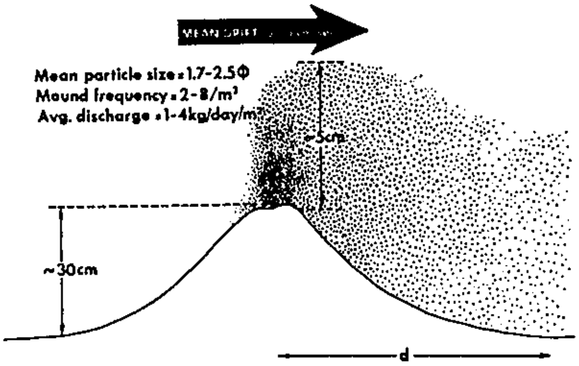

Figure 6. Schematic of *Callianassa*-enhanced sediment transport process. Sediments are ejected an average height of 5 cm into a mean drift of 5-15 cm/sec in sandy bottom areas. Particles of mean size travel a distance *d* downdrift.

ejection was determined by integration of (1). The mean transport rates were determined by multiplying the 3.395 kg/m^2/day of sediment ejected times the average transport velocity times the average settling time. The resulting figures (Table 2) are conservative for the reasons mentioned above.

For comparison, shear velocities obtained from equation (1) were used in Sternberg's technique (1972) to estimate bedload transport under the same ambient, accelerated, and storm conditions. Under ambient conditions the critical threshold velocity for 2.32 ϕ sediment is not attained. It is only marginally attained for accelerated conditions. Under storm conditions bedload transport is much greater than the transport induced by *Callianassa*. It is not at all clear whether these estimates are conservative. The mean sediment size on the bottom may be significantly larger than 2.32 ϕ, the mean size of ejected sediment, thus increasing the transport threshold velocity. The u_* values assumed the presence of mounds; without the mounts, u_* would be less and so would the sediment transport. Conversely, the high-frequency bottom currents associated with waves (Fig. 4) will resuspend sediment and increase the bedload transport.

Most sediment transport will take place over the sandy bottom substrate. Across section A-A' (Fig. 3) the area covered by grass beds is roughly an order of magnitude smaller than by sandy bottom. Total sediment processed is a factor of five less over the grass beds. The larger mean ejected sediment size and smaller ejection height translate to a more rapid settling time over the grass beds. Total transport through the sandy bottom section of A-A' is expected to be approximately two orders of magnitude greater than over the grass beds. Shoreline progradation and progressive widening of the grass beds downdrift (Fig. 3) imply accumulation rather than transport in grassy bottom substrates.

No storm conditions were observed during the 2-week current meter record from the lagoon. Reasonable calculations suggest that the lagoon requires more than an hour of strong wind to come to equilibrium with the new wind stress; thus brief squalls will not be of sufficient duration to cause storm currents. Thus, events of storm intensity are probably infrequent and the bioturbation by *Callianassa* during ambient and accelerated conditions accounts for the bulk of sediment transport through the system.

CONCLUSIONS

Studies in Great Pond Bay, St. Croix, have revealed the important impact of bioturbation by *Callianassa* on sediment transport and habitat modification.

Initial calculations show that under ambient wind, wave, and current conditions, 216 kg/day of sand-sized sediment can be fluxed through a section across the central part of the lagoon. Although bedload transport during major storms can be much higher, conditions sufficient to produce current velocities of storm intensity (as defined in Table 2) occur very infrequently. *Callianassa*-enhanced transport is the dominant process for advecting sediment under normal and moderately accelerated flow conditions.

In addition, intense *Callianassa* bioturbation associates with diminished productivity and cover by sea grasses and algae. High densities of *Callianassa* could be a significant factor in limiting the extent and distribution of sea grass beds in lagoonal environments.

ACKNOWLEDGEMENTS

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