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MODERN CARBONATE SEDIMENT PRODUCTION AND ITS RELATION TO BOTTOM VARIABILITY GRAHAMS HARBOR, SAN SALVADOR, BAHAMAS

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ABSTRACT

In this study, estimates are provided of carbonate production by epibionts on *Thalassia* and five genera of calcareous green algae (*Penicillus, Halimeda, Rhipocephalus, Udotea, Acetabularia*), for a nearshore portion of Graham's Harbor, San Salvador, with emphasis on spatial variability in production associated with bottom variability in carbonate producers.

Field work was conducted during January, 1988 utilizing 11 randomly-spaced north-south transects. Each transect consisted of four stations at 10 meter intervals. At each of the 44 stations, bottom vegetation was censused by counting seagrass blades (*Thalassia, Syringodium, Halodule*) and thalli of macroaglae (*Penicillus, Halimeda, Udotea, Rhipocephalus, Acetabularia*) within a 10 x 20 cm quadrat haphazardly tossed on the substrate. *Thalassia* blades were collected from each station for subsequent laboratory analyses of epibiotic carbonate by Chittick gasometric analysis.

Preliminary results estimate the annual carbonate sediment production in the study area by calcareous green algae and epibionts on *Thalassia* to be 136 $g/m^2/y$. Principle contributors to carbonate sediment accumulation include *Halimeda* (58 $g/m^2/y$), *Penicillus* (38 $g/m^2/y$), and epibionts on *Thalassia* (28 $g/m^2/y$). Bottom cover within Graham's Harbor is patchy on a small scale, and the bottom variability results in a highly variable rate of carbonate production.

INTRODUCTION

Purpose

Previous studies of carbonate sediment production associated with seagrass ecosystems have generally been limited in both their treatment of spatial variability in bottom composition and the diversity of carbonate producers evaluated. The principal contribution of this study is to provide estimates of carbonate production by epibionts on *Thalassia*, and five genera of calcareous green algae (*Penicillus, Halimeda, Rhipocephalus, Udotea, Acetabularia*), for a nearshore portion of Graham's Harbor, San Salvador. Emphasis will be given to the relationship between carbonate production rates and the variable nature (i.e., spatial patchiness) of the bottom.

Background

Substantial research has been conducted on the productivity of modern carbonate banks. Lowenstem (1955) was among the first to propose an allochemical origin for lime muds, mainly through the post-mortem disintegration of lightly calcified green and red algae. The first rigorous attempt to quantify the contribution of algal sources to Holocene carbonates was provided by Stockman *et. al.* (1967), who concluded that production by the green alga *Penicillus* was by itself more than adequate to account for the amount of Holocene lime mud observed in south Florida.

Neumann and Land's (1975) study in the Bight of Abaco introduced the concept of a modern "carbonate budget". They found that all of the Holocene lime mud presently within the basin could be derived from four common algal genera (*Penicillus, Halimeda, Rhipocephalus*, and *Udotea*), and, further, that there is a significant overproduction of sediment by these sources relative to the amount of material presently contained in the Bight of Abaco Basin.

Algal studies stimulated research on the relative contribution of other calcified plants and animals to Holocene sediments. Land (1970) undertook a study in Discovery Bay, Jamaica, in which he quantified the sediments produced from the post-mortem decay of *Thalassia* blades, and the subsequent release of epibionts (mainly red algae and serpulid worms) to produce lime mud. Patriquin (1972) established a similar estimate for a *Thalassia* meadow in Barbados. Nelson and Ginsburg (1986) quantified lime mud production by *Thalassia* epibionts in Florida Bay (same study area as Stockman *et. al.*, 1967). Each of these studies indicated that production by epibionts on *Thalassia* may equal or exceed that of calcareous green algae as a source of fine carbonate.

Numerous other investigations have attested to the significance of calcareous green algae as producers of carbonate sediment. Bach (1979) studied the carbonate sediment production of four calcareous green algae genera, (*Halimeda, Penicillus, Rhipocephalus*, and *Udotea*), in Card Sound, south Florida. Wefer (1980) estimated production by the green algae *Halimeda* and *Penicillus*, as well as, the brown alga *Padina*, in Harrington Sound, Bermuda. Bosence *et. al.* (1985) studied a modern carbonate mud mound in the Florida Keys, and established sediment production estimates for the green algae *Halimeda, Penicillus*, and *Acetabularia*, as well as for epibionts on *Thalassia*, molluscs, and two genera of coral.

Despite the magnitude of this earlier work, small-scale variations in benthic environments, and potentially associated variations in carbonate production rates, have often been ignored. Thus, production rates calculated for a single location, or for widely spaced localities, are often extrapolated to perhaps unrealistically large areas of the seafloor. In contrast, this study establishes carbonate production rates for both green algal and epibiotic carbonate sources for a relatively confined study area, while considering the small-scale variable nature (i.e., spatial patchiness) of the bottom.

STUDY AREA

Graham's Harbor is a windward, high energy lagoon, located at the northeastern end of San Salvador (Fig. 1). This shallow basin is bounded by San Salvador to the south, and North Point to the east. A barrier reef protects the lagoon along its northern margin, and it is open to deeper waters to the west. The study area incorporates a nearshore *Thalassia*-dominated environment that covers approximately 2 x 10^5 m^2. Maximum water depth within the study area is 3 m; Colby and Boardman (1988) have determined

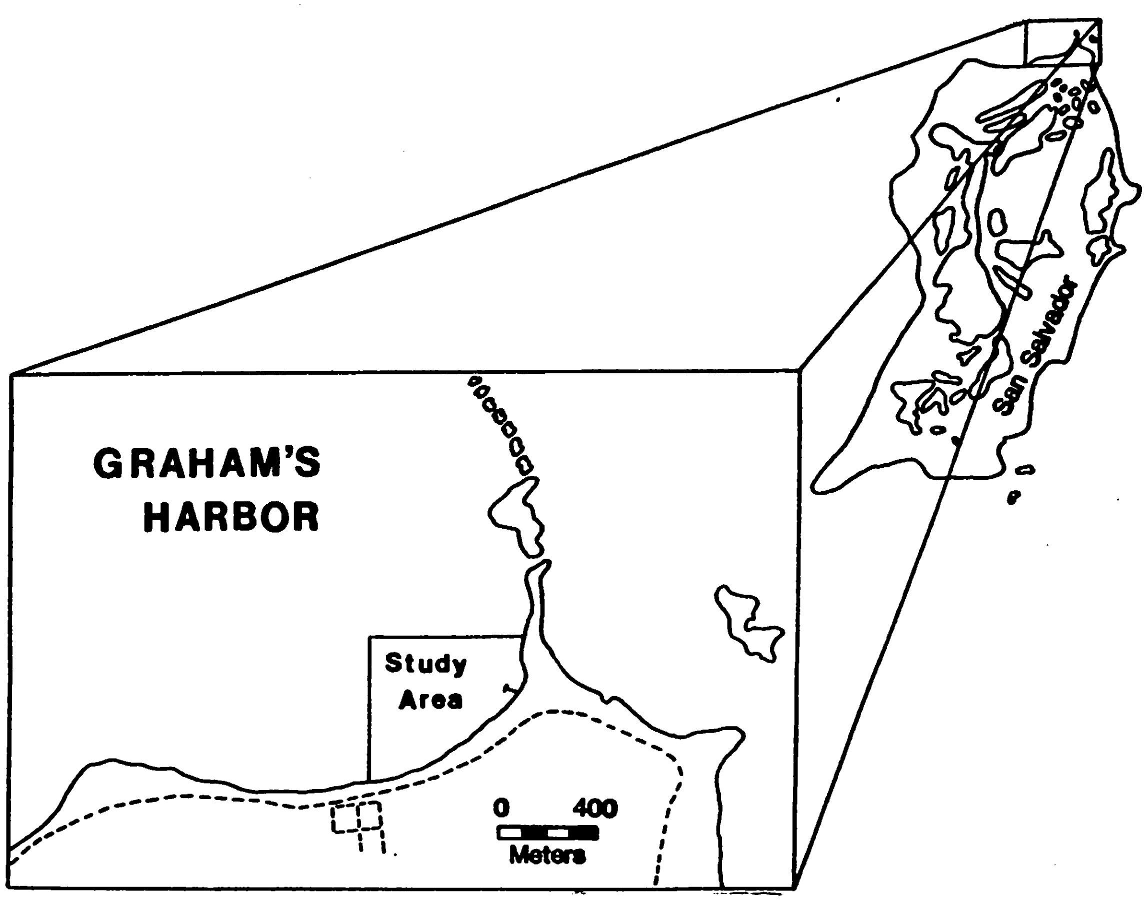

Fig. 1. Map of Graham's Harbor, located at the northeastern end of San Salvador; note the limits of the study area within Graham's Harbor.

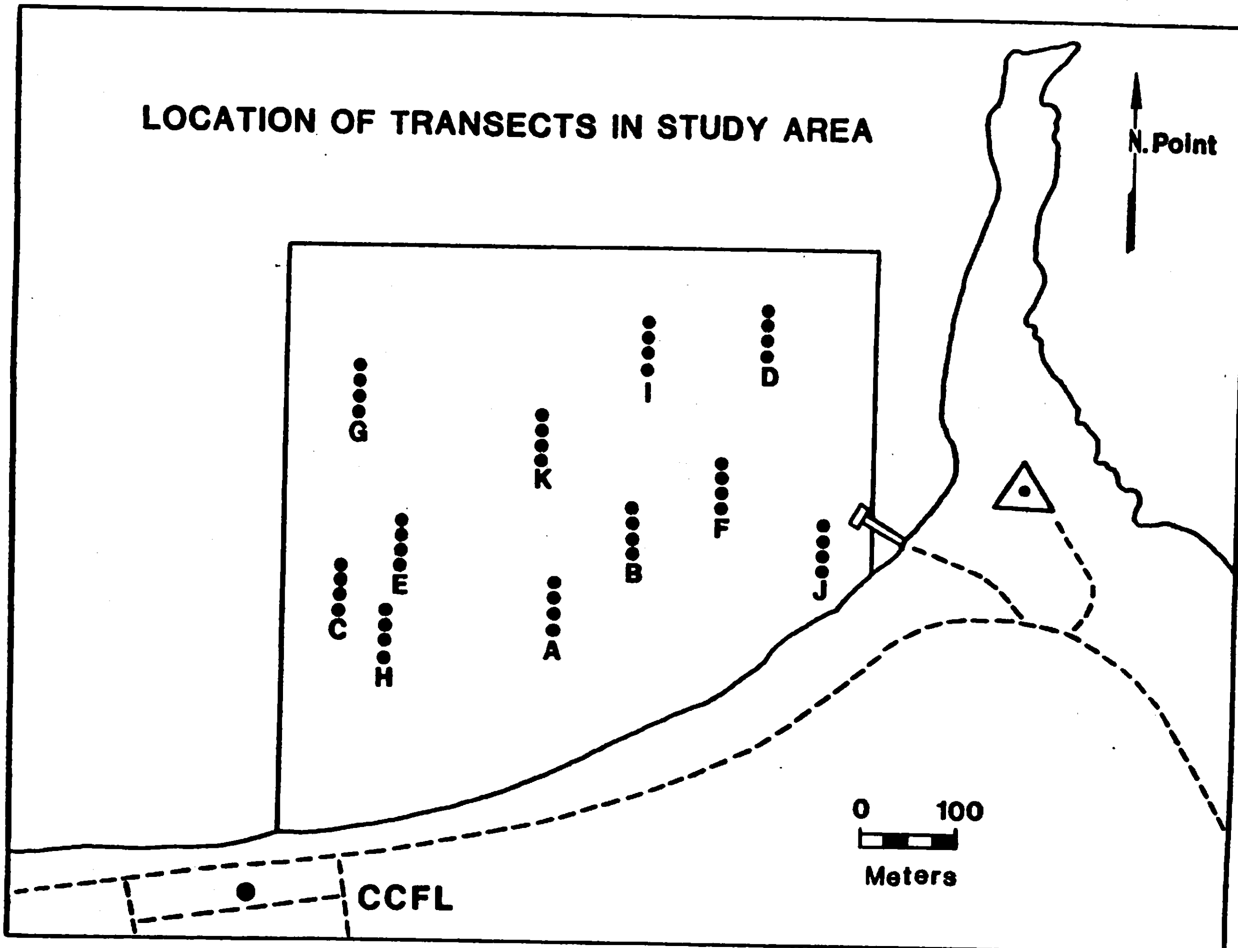

Fig. 2. Map displaying the location of transects within the study area. Transects are oriented north-south, and spaced to sample the entire study area.

the maximum water depth within the remainder of Graham's Harbor to be about 6 meters.

Colby and Boardman (1988) have reported on the texture, mineralogy, and grain types of Holocene sediments within Graham's Harbor. Sediment thickness reportedly varies between 1.5 and 4 m, and studies of sediment cores have indicated a coarsening upward sequence for these deposits.

Peat samples recovered from immediately above the Pleistocene bedrock have been radiocarbon dated and indicate initial flooding of Graham's Harbor approximately 5000 y.b.p. Colby and Boardman (1988) have used sediment thickness, along with peat dates, to estimate a Holocene rate of sediment accumulation of between 30 and 80 cm/1000 years.

METHODS

Field Methods

Field work was conducted during January, 1988. A second field season was carried out during June, 1988 to assess the impact of seasonality on epibiont and macroalgal sediment production; results of this summer field work are not included in this report.

Within the study area, censusing of macroflora was accomplished utilizing 11 transects oriented north-south; transects were spaced so that the entire study area was covered (See Fig. 2). Each transect consisted of four stations at 10 meter intervals. At each station, a 10 x 20 cm. quadrat was haphazardly tossed on the substrate, and bottom vegetation was censused by counting grass blades (*Thalassia, Syringodium, Halodule*) and thalli of macroalgae (*Penicillus, Halimeda, Udotea, Rhipocephalus*, and *Acetabularia*) within this quadrat. This procedure was repeated eight times at each station to determine station-level variations in abundance.

Approximately 60 *Thalassia* blades were collected from each station by clipping the blades at the sediment-water interface. Thereafter, *Thalassia* blades were dried and bagged for subsequent laboratory analysis of epibiotic carbonate.

Laboratory Analysis

Laboratory analysis of epibiotic carbonate on *Thalassia* blades was accomplished by CO_2 evulsion in a Chittick gasometric apparatus (Dremanis, 1962). This apparatus measures the volume of CO_2 evolved by reacting grass blades with 6M HCl. Using weighed quantities of standard $CaCO_3$, the apparatus was calibrated based on the volume of $CaCO_3$ evolved. A correlation coefficient (r) between $CaCO_3$ reacted, and CO_2 evolved, was calculated as .99, attesting to the accuracy of the method.

Production Calculations

Fig. 3 illustrates the series of steps involved in the calculation of annual carbonate sediment production from census data. The eight rectangles in the upper left corner of the diagram represent the eight values obtained by repetitive censusing at each station. Census values for each repetition are averaged, and a mean for the standing crop of each organism/station is obtained (Step 1 in Fig. 3). Annual carbonate production rates are generally reported as g $CaCO_3/m^2/y$, and the area within a 10 x 20 cm. quadrat is .02 m^2. Thus, the mean abundance of each organism at each station must be multiplied by 50 to determine the number of organisms/m^2 (Step 2 in Fig. 3).

Next, these values are multiplied by the weight (in grams) of $CaCO_3$ produced by post-mortem, disintegration of green algae (Step 3a in Fig. 3), or release of epibionts from *Thalassia* blades (Step 3b in Fig. 3). Values for calcification per alga were obtained from the literature (Table 1, depicted by a periodical in Fig. 3), and for carbonate associated with epibionts by Chittick gasometric analysis (depicted by the schematic Chittick apparatus in Fig. 3).

Finally, this value must be multiplied by the estimated turnover rate for the organism being considered. The turnover rate for a particular

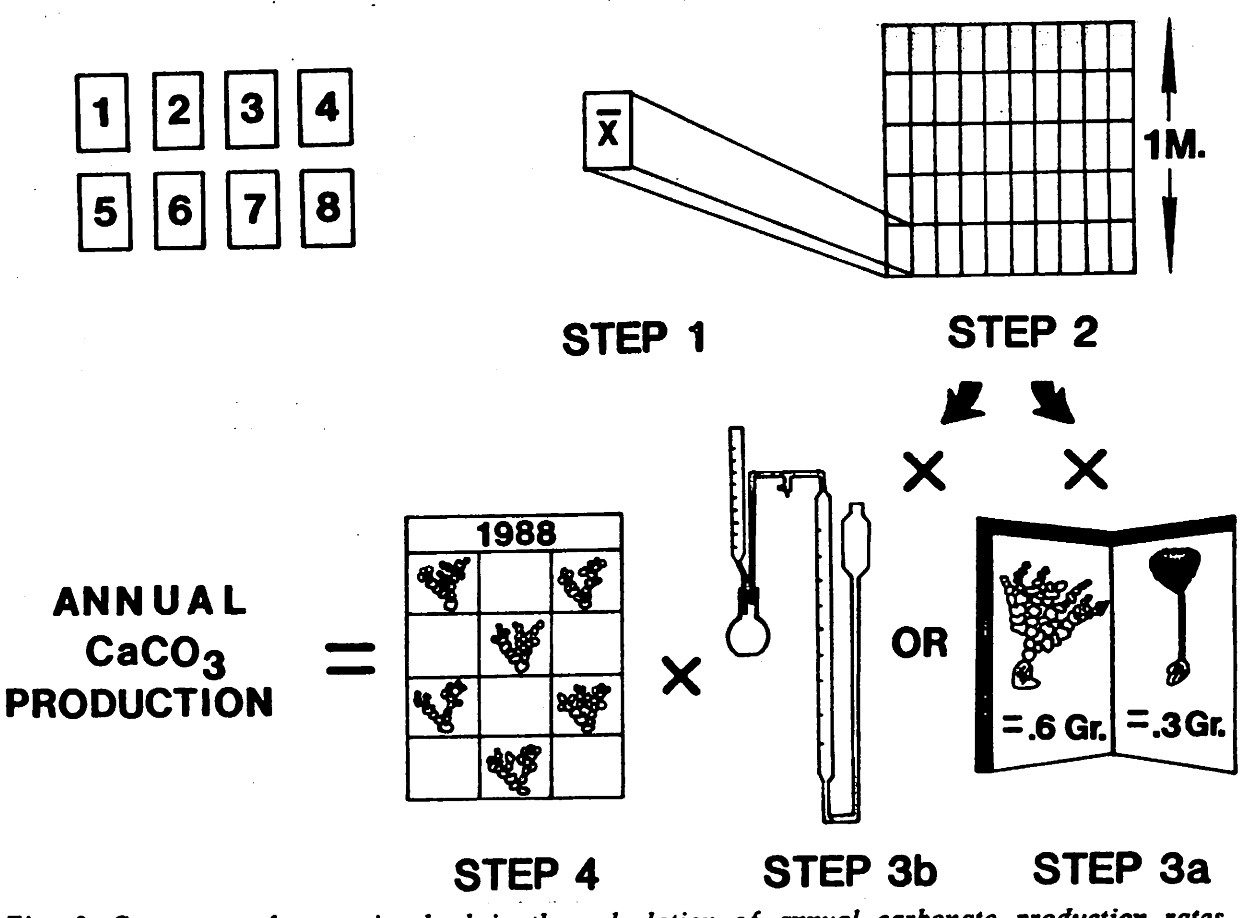

Fig. 3. Summary of steps involved in the calculation of annual carbonate production rates from census data.

Table 1: Production values for various carbonate producing organisms.

	NELSON (1986)	STOCKMAN (1967)	NEUMANN (1975)	BACH (1979)	WEFER (1980)	BOSENCE (1985)	MARSZALEK (1975)	THIS STUDY (1988)
Thalassia								
Turn Over	6 crops	---	---	---	---	---	---	6 crops
Penicillus								
Turn Over	---	6-9 crops	6-12 crops	68 days	4 crops	5 crops	---	6 crops
Calcification	---	.17-.52 g	.274 g	---	---	---	---	.274 g
Halimeda								
Turn Over	---	---	6-12 crops	---	7 crops	2 crops	---	6 crops
Calcification	---	---	.628 g	---	---	---	---	.628 g
Rhiphocephalus								
Turn Over	---	> P. cap.	6-12 crops	50 days	---	---	---	6 crops
Calcification	---	---	.413 g	---	---	---	---	.413 g
Udotea								
Turn Over	---	---	6-12 crops	87 days	---	---	---	6 crops
Calcification	---	---	.213 g	---	---	---	---	.213
Acetabularia								
Turn Over	---	---	---	---	---	---	3-5 crops	4 crops
Calcification	---	---	---	---	---	---	74 %	74%

organism is based on the number of times its standing crop is thought to replicate itself each year (Table 1; step 4 in Fig. 3). Thus, $CaCO_3$ production, for each organism at each station, is determined as follows:

$$\text{Annual } CaCO_3 = \bar{X}*50*(gr.CaCO_3/organism)*\text{turnover rate}$$

RESULTS AND DISCUSSION

Standing Crops

The average abundance of seagrasses and calcareous green algae (standing crop) are summarized in Table 2. Upon casual observation of the substrate, the wider-bladed variety of seagrass, *Thalassia*, may appear to be more prevalent than *Syringodium* or *Halodule*. Census work reveals that *Syringodium* is actually the most abundant variety of seagrass, with an average abundance of 810 blades/m^2. *Thalassia* is substantially less abundant, with an average density of 516 blades/m^2. *Halodule* averaged 170 blades/m^2.

Table 2: Standing crops of Seagrasses and calcareous green algae, January 1988

SEAGRASSES	RANGE/M^2	AVERAGE/M^2
Syringodium	0-1587	810 +/- 124
Thalassia	0-1156	516 +/- 78
Halodule	0-806	170 +/- 53
MACROALGAE		
Penicillus	0-43	23 +/- 5
Halimeda	0-94	15 +/- 7
Acetabularia	0-43	6 +/- 4
Rhipocephalus	0-31	3 +/- 2
Udotea	0-13	3 +/- 2

Penicillus was determined to be the most abundant genus of green algae with an average estimated abundance of 23 plants/m^2. Less common genera include *Halimeda* at 15 plants/m^2, *Acetabularia* at 6 plants/m^2, *Rhipocephalus*, and *Udotea* (both averaging 3 plants/m^2).

Bottom Variability

Fig. 4 is a map of the study area that illustrates the relationship in floral composition of sample localities, as determined by Q-mode cluster analysis. Q-mode cluster analysis is a multivariate statistical technique, that hierarchically groups samples together on the basis of similarities in composition within a given data set.

Initially, (as seen in Fig. 4) all floral variables were considered, and the 44 stations were grouped into four clusters: *Halodule*-dominated, *Syringodium*-dominated, *Thalassia*-dominated, and Intermediate. Fig. 4 suggests some degree of non-randomness in the distribution of bottom types within the study area, in that a few transects are dominated by the same bottom type at three or four stations. However, other transects are more highly variable.

In Fig. 4 the substantially greater abundances of seagrass blades relative to macroalgae,

CLUSTER ANALYSIS MAP: ALL FLORAL DATA

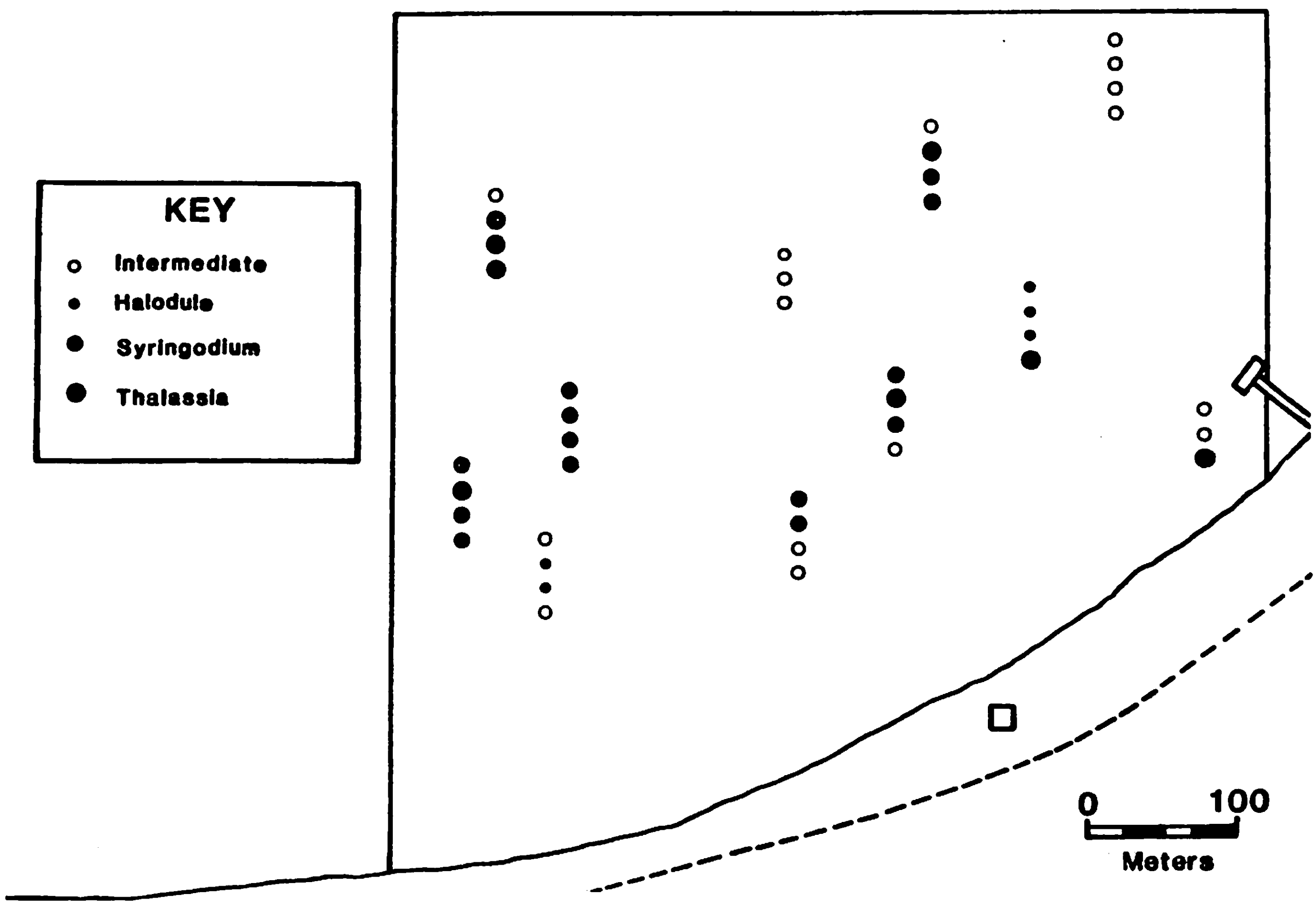

Fig 4. Distribution of census stations determined by cluster analysis to have similar faunal compositions. All floral variables are considered; blank stations denote areas of bare sand.

effectively overshadowed recognition of bottom variability in macroagal abundances. Clusters (bottom types) were determined primarily by similarities in abundances of seagrass genera. Thus, a second cluster analysis was conducted using macroalgal data only. Fig. 5 is a map showing the distribution of stations determined by Q-mode cluster analysis to have similar macroalgal bottom types. As with seagrasses, clustering of macroalgal bottom types suggests a pattern that is not entirely random. Certain macroalgal bottom types persist on the scale of 2 or 3 stations, but more generally, the distribution shows little or no pattern.

Production Rates

Epibionts on *Thalassia*

The annual production associated with epibionts on *Thalassia* has been calculated using data for standing crop (from census work), epibionts per blade of *Thalassia* (from Chittick analysis), and turnover rates (from literature), to be 28 g $CaCO_3/m^2/y$, with a range at individual stations of 0 to 68 g $CaCO_3/m^2/y$. Production varies substantially even on the scale of individual transects (40 meters), and there do not appear to be any onshore-offshore or east-west gradients in epibiont production.

Table 3 compares epibiont production in Graham's Harbor to that reported for other modern carbonate banks. The epibiont production estimated for January 1988 in Graham's Harbor is approximately five times less than that reported by Land (1970) in Discovery Bay, Jamaica, approximately three times less than that reported by Nelson and Ginsburg (1986) (for areas of similar *Thalassia* density) in Florida Bay, and two orders of magnitude less than that reported by Patriquin (1971) for Barbados.

When samples collected in June are analyzed, production values may be more in line with

CLUSTER ANALYSIS MAP: MACROALGAE ONLY

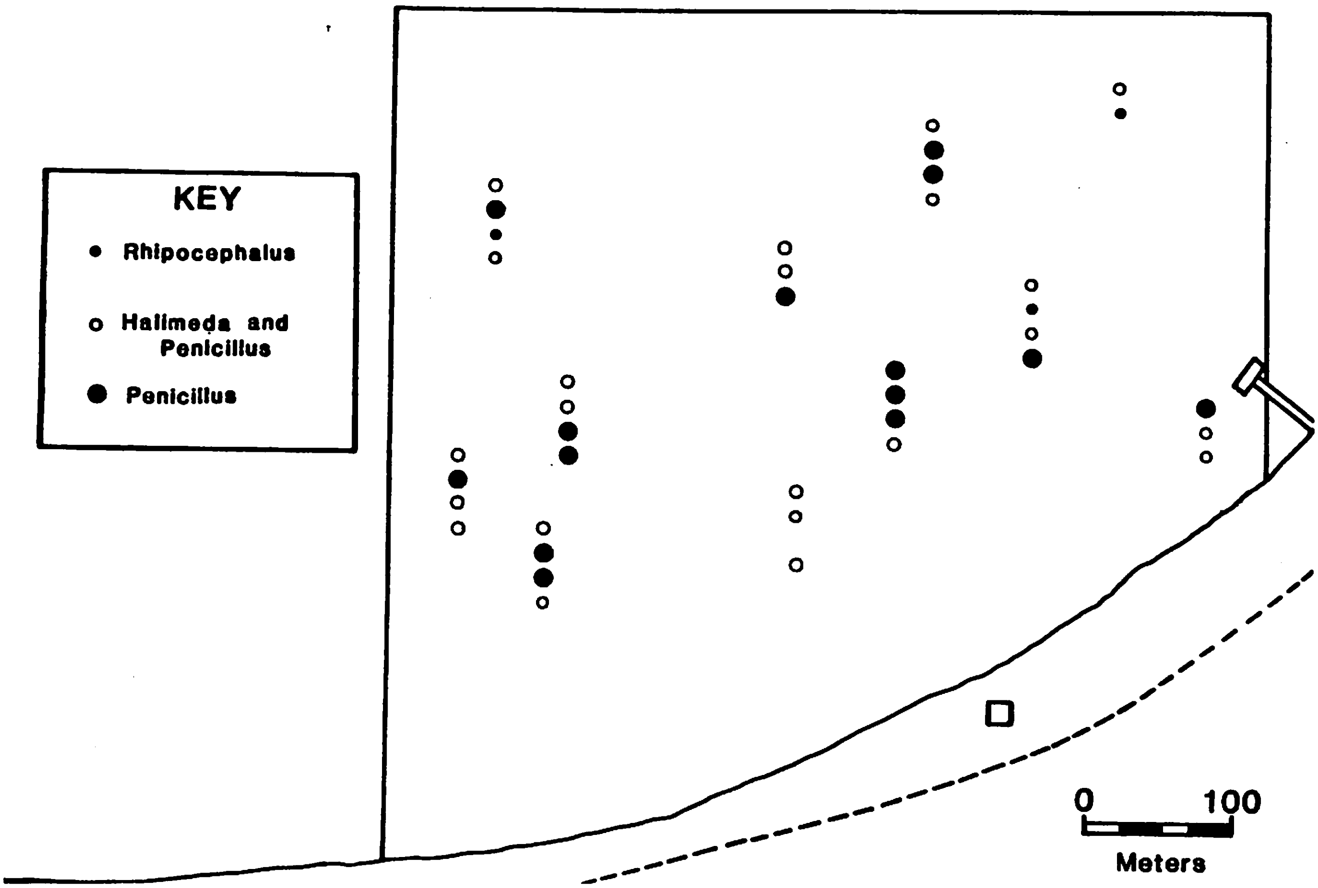

Fig. 5. Distribution of census stations determined by cluster analysis to have similar faunal compositions. Only green algal genera considered; blank stations denote areas with no algal plants.

others reported in the literature. However, preliminary results suggest that production will increase only slightly above that estimated with just the January data. The disparities between epibiont production rates reported here and those of previous authors may be the consequences of differences in *Thalassia* (eg. Land, 1970), lagoonal circulation and energy (eg. Nelson and Ginsburg, 1986) and methodology (Patriquin, 1971).

Green Algae

The annual production associated with various genera of green algae has been calculated using data for abundance (from census work), data for weight of carbonate/plant (from the literature), and turnover rates (from the literature). Although the abundance of *Halimeda* was found to be less than that of *Penicillus*, carbonate production associated with *Halimeda* was greater (58

Table 3: Comparison of reported carbonate production rates associated with epibionts on Thalassia.

AUTHOR	LOCATION	$g/CaCO_3/m^2/y$
Patriquin (1972)	Barbados	2800
Land (1970)	Jamaica	180
Nelson & Ginsburg (1986)	Florida Bay (Entire Field Area)	118
	Florida Bay (0-1000 Blades/m^2)	73
** This Study (1988)	Graham's Harbor	28 +/- 6

g $CaCO_3/m^2/y$). This discrepancy results from the greater mass of skeletal carbonate associated with *Halimeda*, compared to *Penicillus*.

Production of sediment associated with *Penicillus* averaged 38 $g/m^2/y$ across the study area. Other green algal genera contributing to annual sediment production included *Rhipocephalus* (6 g $CaCO_3/m^2/y$), *Udotea* (3 g $CaCO_3/m^2/y$), and *Acetabularia* (1 g $CaCO_3/m^2/y$). At most stations these last three genera were absent or rarely present, but occasionally *Rhipocephalus* and *Udotea* were significant contributors, with production rates as high as 60 g $CaC0_3/m^2/y$, and 26 g $aC0_3/m^2/y$, respectively. Marszalek (1975) reported that periodic blooms of *Acetabularia* contribute significantly to local sediment accumulation; no *Acetabularia* blooms were observed during field work, and thus, production by this genus was minimal.

Table 4 compares the carbonate production associated with calcareous green algae to that reported by previous authors. Production associated with *Halimeda*, *Penicillus*, *Rhipocephalus*, and *Udotea* is comparable or sightly larger than that reported by Neumann and Land (1975) in the Bight of Abaco, and within the range of values reported for the Florida Keys and other areas.

Total Carbonate Production

The total carbonate sediment production in Graham's Harbor is estimated to be 136 g $CaCO_3/m^2/y$, (detailed in Table 5). It is recognized that this value may be subject to seasonal fluctuations (Bach, 1979; Wefer, 1980). Such variability will ultimately be accounted for using data collected during the summer of 1988.

Fig. 6 is a map showing the variability of total carbonate production rates within the study area. This figure conveys the high degree of spatial variability in carbonate production which can exist even between such closely-spaced census localities. Thus, for *Thalassia*-dominated lagoonal environments, as well as other localities and depositional environments exhibiting a high degree of spatial variability in carbonate producers, it is suggested that census data for single stations not be extrapolated to extensive areas of that environment.

How does total carbonate production in Graham's Harbor compare to that of other localities and environments of modern carbonate deposition? Direct comparison is difficult; Neumann and Land did not consider epibiont production in the Bight of Abaco, and even with the combination of production estimates from Stockman et. al.

Table 4: Comparison of reported carbonate production rates associated with calcareous green algae.

GENUS/AUTHOR	LOCATION	g $CaCO_3/m^2/y$
Halimeda		
Bosence (1985)	Florida Keys	105
** This Study (1988)	Graham's Harbor	58 +/- 25
Neumann & Land (1975)	Bight of Abaco	24-48
Bach (1979)	South Florida	2-11
Penicillus		
Bosence (1985)	Florida Keys	135
** This Study (1988)	Graham's Harbor	38 +/- 8
Neumann & Land (1975)	Bight of Abaco	22-44
Wefer (1980)	Bermuda	30
Stockman & Ginsburg (1967)	Inner Reef Tract	25
	Florida Bay	3
Bach (1979)	South Florida	1-3
Rhipocephalus		
** This Study (1988)	Graham's Harbor	8 +/- 6
Neumann & Land (1975)	Bight of Abaco	2-3
Bach (1979)	South Florida	1-2
Udotea		
Bach (1979)	South Florida	.1-6
Neumann and Land (1975)	Bight of Abaco	2-4
** This Study (1988)	Graham's Harbor	3 +/- 2
Acetabularia		
Marszalek (1975)	Florida Keys	720
** This Study (1988)	Graham's Harbor	0.5 +/- .3

Table 5: Total carbonate sediment production, Graham's Harbor, January, 1988

SOURCE	$g\ CaCO_3/m^2/y$
Halimeda	58
Penicillus	38
Epibionts on Thalassia	28
Rhipocephalus	8
Udotea	3
Acetabularia	1
Total	136

(1967), and Nelson and Ginsburg (1986), data are still lacking for *Halimeda* and other major green algal sources in Florida Bay. Clearly, more study is needed to see how total carbonate sediment rates vary with locality, space, and time.

Bosence (1985) has produced one of the most comprehensive studies of carbonate sediment production to date. He estimated sediment production for all major producing organisms on Tavernier mound (a modern carbonate mound in the Florida Keys) to be 500 $g/m^2/y$. While considerably higher than the value calculated in the present study, such a high rate might be expected because carbonate mounds occupy the end spectrum of reefs, an environment known to be populated by exceedingly high carbonate producers (Stern, *et. al.*, 1977).

CONCLUSIONS

Annual carbonate production by calcareous green algae and epibionts associated with *Thalassia* is estimated at 136 $g/m^2/y$ for a 3.6×10^5 m^2 area of Graham's Harbor. Principle contributors to carbonate sediment accumulation include *Halimeda* (58 $g/m^2/y$), *Penicillus* (38 $g/m^2/y$), and epibionts on *Thalassia* (28 $g/m^2/y$).

Comparison with previous studies suggests

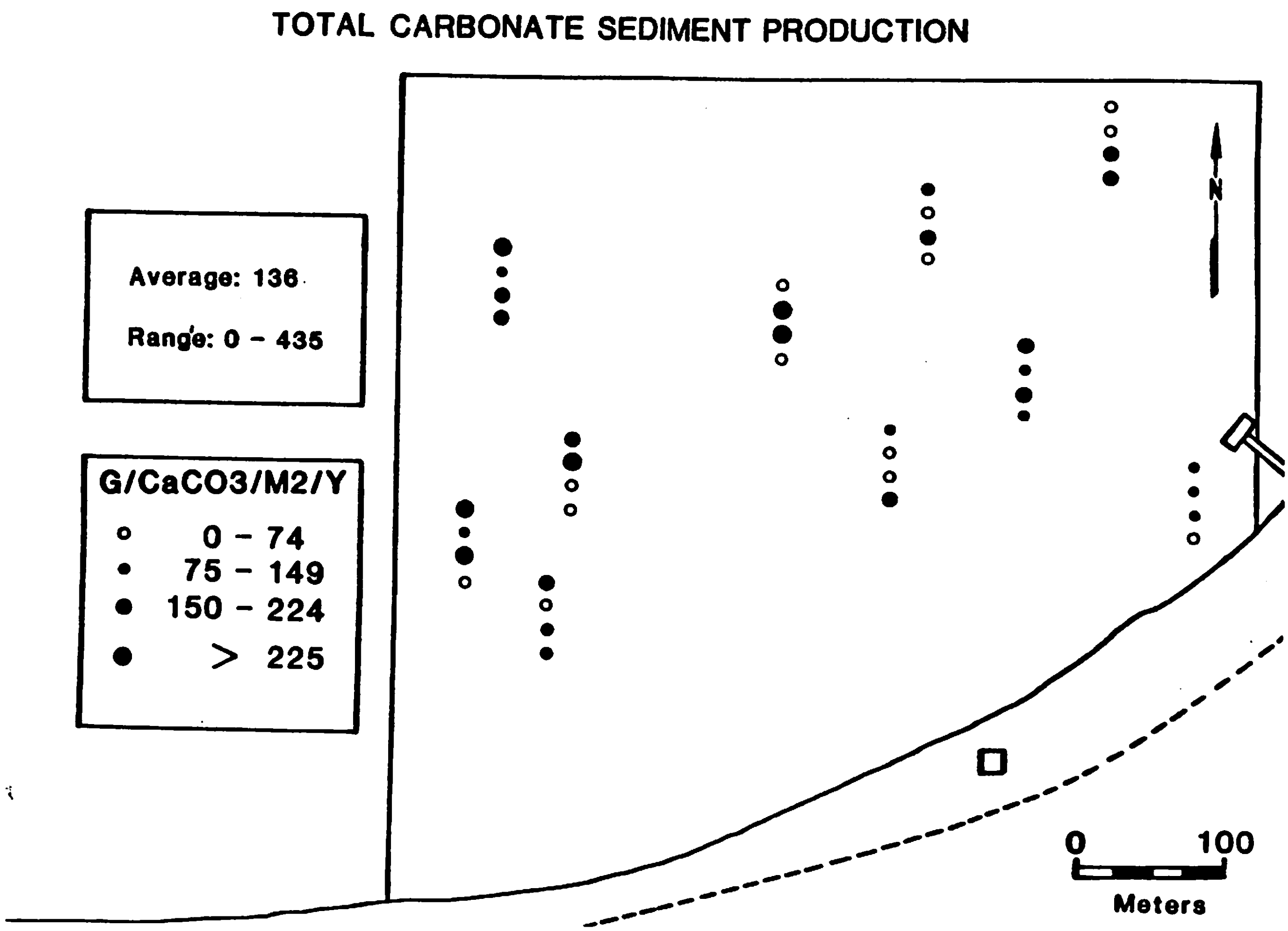

Fig. 6. Map of the study area which illustrates the variability of total carbonate production within the study area. Transect A is not represented because values for epibionts on Thalassia *were not obtained.*

that carbonate production associated with epibionts on *Thalassia* is approximately three times less than that reported for similar *Thalassia*-covered bottoms in Florida Bay, and is substantially less than those values reported for Jamaica, and Barbados. Carbonate production associated with various macroalgae is comparable to sightly higher than that reported in the Bight of Abaco, and within the range of values reported for other areas.

Substantial insight into the production variability within a modern lagoonal environment can be determined by closely spaced sampling. Bottom cover within Graham's Harbor is patchy on a small scale, and the bottom variability results in a highly variable rate of carbonate production. This suggests that production rates determined at individual sampling and census sites should not be extrapolated far beyond the bounds of such stations.

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