A Preliminary Evaluation of Wave Attenuation by Four Species of Seagrass

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Seagrasses are able to modify current flow and sediment composition, yet little information exists describing their effect on waves. Four species of seagrass, *Halodule wrightii*, *Syringodium filiforme*, *Thalassia testudinum* and *Zostera marina* were evaluated for their ability to reduce wave energy under various combinations of shoot density and water depths over a 1 m test section in a wave tank. Percent wave energy reduction per meter of seagrass bed equaled 40% when the length of these seagrasses was similar to the water depth. Seagrasses are approximately equal to saltmarshes in reducing wave energy on a unit distance basis, but only when water depth is scaled to plant size. When seagrass beds occur as broad, shallow meadows, the influence of seagrasses on wave energy will be substantial.

Introduction

Although seagrasses are widely recognized for their ability to modify tidal currents (Molinier & Picard, 1952; Ginsberg & Lowenstam, 1958; Scoffin, 1970; Schubel, 1973; Orth, 1977; Wanless, 1981; Fonseca *et al.*, 1982; 1983; Peterson *et al.*, 1984; Fonseca & Fisher, 1986; Fonseca & Kenworthy, 1987; Fonseca, 1989; Gambi *et al.*, 1990) little is known about their capacity to influence waves. In contrast, the reduction of wave energy in salt marshes (*Spartina alterniflora*) has been quantified (Knutson *et al.*, 1982). *S. alterniflora* marshes can decrease incoming wave energy by approximately 26% per meter of vegetation. This may play a substantial role in structuring the marsh-associated plant and animal communities.

Seagrass cover decreases physical stress on the sediment-water interface (Fonseca *et al.* 1982, 1983; Fonseca & Fisher, 1986; Gambi *et al.*, 1990). Wayne (1975) noted wave height reduction by *Thalassia testudinum* in the Gulf of Mexico. Suspended particulate material (SPM) concentrations were found to be lower within seagrass beds compared to unvegetated sand flats (Ward *et al.*, 1984). As water levels were elevated above the canopy height, wave height was less affected and particulate material was resuspended, but

concentrations were still lower than in unvegetated areas. Ward *et al.* (1984) concluded that sedimentation rates were significantly higher in the seagrass community than in unvegetated areas.

Heller (1987) found that reduction of mean fluid velocities within the seagrass canopy was a function of current speed, wave frequency, distance into the meadow, and seagrass species. In that study, *Syringodium filiforme* was most effective at reducing fluid velocity in low current regimes (5–16 cm . s^{-1}) while *T. testudinum* was most effective in a medium current regime (23–40 cm . s^{-1}). When exposed to unidirectional flow alone, seagrasses reduce water motion through the canopy, although the relative effectiveness of each species may differ (Fonseca and Fisher, 1986). With the exception of *S. filiforme* which is nearly cylindrical, all of these species are strap-bladed. Taken together, these studies serve to confirm that seagrasses have the potential to significantly modify sedimentation regimes when exposed to waves or currents as well as the combination of the two.

Seagrasses have recently become of interest due to the roles they play in increasing sediment stability in anthropogenically disturbed areas. With increasing numbers of vessels using the intracoastal waterways of the U.S., the reduction of boat wake wave energy by these plants is suspected to be an important factor in reducing boat wake-associated sediment resuspension. Reduction of sediment resuspension maintains a lower ambient turbidity in the water column as shown by Ward *et al.* (1984), a factor critical to the continued survival of the seagrasses and their associated community (Kenworthy & Haunert, 1991). Reduction of anthropogenically-derived wave energy by seagrasses should lower shoreline erosion rates as well.

In this paper, we provide preliminary data on wave energy reduction by four common North American seagrass species (*Halodule wrightii*, *S. filiforme*, *T. testudinum*, and *Zostera marina*). To provide a context for the role of seagrasses in coastal systems, we compare our estimates of wave height reduction with those of Knutson *et al.* (1982) for saltmarshes.

Methods

H. wrightii, *S. filiforme*, and *T. testudinum* are sympatric over most of their range in the United States which extends from the east coast of Florida and throughout the Gulf of Mexico. *Z. marina* only co-occurs with *H. wrightii* at the southern extreme of its range in North Carolina where a population of *H. wrightii* occurs in isolation from the rest of its distribution with the other tropical seagrasses which begin in Florida. Live *H. wrightii*, *S. filiforme*, and *T. testudinum* were collected as intact sods from several sites along the Florida Keys and transported in water-filled containers to the Beaufort Laboratory within 36 h for testing. *Z. marina* sods were collected in North Carolina near Beaufort. These were the same individual plants used for unidirectional current studies by Fonseca and Fisher (1986).

A wave tank/flume apparatus (Fonseca & Fisher, 1986) was used for evaluation of wave energy reduction. Sods of a given species were placed in a depressed section of the tank floor to form a 1·0 m long × 0·23 m wide test section. The tank was 6·10 m long 0·23 m wide and 0·46 m deep with the test section 4·0 m from the wave generator. The tank floor, including the sediment surface of the test section, was covered with 0·5 mm mean diameter siliceous sand which was leveled between trials.

Three randomly selected 100 cm^2 quadrats were harvested from each test section after the wave trials were completed for each seagrass species. Average leaf lengths per quadrat were measured from the sediment surface to the distal portion of the longest leaf of each shoot and represented naturally-occurring density ranges (Table 1).

TABLE 1. Leaf lengths and short shoot densities for the species tested. (−) = data not available

	Leaf length (cm)	Shoots/m²
H. wrightii	17·2	2870, 2600, 1900
S. filiforme	41·4	1350, 570, 230
T. testudinum	19·4	1500, 1050, 850
Z. marina	23·4	1000, 750, −

Each density of each seagrass species was exposed to two types of waves, one with a mean period of 0·7 s and wavelength of 68 cm and another with a mean period of 0·4 s and wavelength of 37 cm. These were generated in different water depths for each seagrass species:

	Water depths
H. wrightii:	6, 9, 12
S. filiforme:	18, 19, 30
T. testudinum;	9, 10, 12, 14
Z. marina:	12, 19 (cm).

Given that leaf length was constant within a species, the water depths were selected to approximately double the water depth/leaf length ratio within a species. These wave conditions represented the most stable wave forms which the apparatus could generate. The waves used in this study were within the lower end of the range of wave conditions found in 91 field observations in seagrass beds, near Beaufort, N.C., taken during routine field work:

	Minimum	Maximum	Mean	SE
Wave height (cm)	1·0	20·0	6·0	0·397
Period	0·6	3·0	1·6	0·049
Wavelength	56·0	1400·0	417·0	26·900

Taking into account that these data are likely biased toward favorable working conditions, our findings represent only a narrow range of the conditions to which seagrass beds are exposed.

The change in wave height as a wave passed through the 1 m test section of seagrass was recorded under each combination of water depth, density and species. The paddle wave-generator produced a wave train where the fifth wave generated varied <5% in height during pre-study trials. A photograph of the fifth generated wave was taken at a known scale as it entered the meadow. The wave generator was then turned off, the camera moved to the end of the 1 m test section and the water surface allowed to become still. The wave generator was then restarted and the fifth generated wave was photographed leaving the test section. Measurements of wave height entering and leaving the test section were obtained from these photographs by projecting them onto a scaled grid.

Measures of wave height change across the test section without seagrass were used as a control. No changes in wave heights could be measured across the range of water depths (unvegetated bottom) used in this study (6–30 cm).

Wave heights were converted into energy density ($E = $ Joules . m^{-2}) using the equation for linear waves (Denny, 1988):

$$E = (1/8)(rho)gH^2 \tag{1}$$

where: rho = density of seawater (1025 kg . m^{-3})
   g   = gravity ($9 \cdot 8$ m . s^{-2})
   H   = wave ht (m).

Plant densities were chosen for each species to reflect field conditions. Water depths were chosen so as to be scaled to plant size, hence a non-orthogonal data set was created, preventing statistical comparisons among species. To produce an orthogonal data set, each of the seagrass species would have to have been tested over identical combinations of density and water depth. Because these species naturally differ in blade length, the orthogonal approach would have produced some problems in scaling both the amount of wave energy encountered at a given depth in the water column (vertical wave energy distribution being non-linear) and amount of plant material in a given amount of water. Therefore, we manipulated water depth so that the water depth/leaf length ratios varied within each species (*H. wrightii* $0 \cdot 35$ to $0 \cdot 70$; *S. filiforme* $0 \cdot 72$ to $1 \cdot 20$; *T. testudinum* $0 \cdot 55$ to $0 \cdot 73$; *Z. marina* $0 \cdot 65$ to $1 \cdot 03$).

Effects of leaf length, water depth and shoot density were evaluated using ANOVA for their effect on wave energy density reduction using the percent reduction in energy density over the 1 m test section where,

$$\text{Wave Energy Reduction} = [\{E \text{ (in)} - E \text{ (out)}/E \text{ (in)}\}*100] \cdot m^{-1} \tag{2}$$

E (in)   = energy density entering the 1 m test section
E (out) = energy density leaving the 1 m test section.

An F-max test on arcsine-transformed (Sokal & Rohlf 1969) percent energy reduction was performed to test for heteroscedacity prior to ANOVA. Species were compared graphically and with regression analysis for percent energy reduction as a function of leaf length, water depth, seagrass stem density and initially, wave type. No effect of wave type on change in wave height across the test section was detected and wave type was subsequently disregarded in the analysis. Finally, the relation of percent energy reduction to the interaction of leaf length and water depth was evaluated by developing a 3-dimensional graphic using SAS (SAS 1987) smoothed spline interpolation.

Results

The average wave heights entering and exiting the test sections are provided in Table 2 by seagrass species. However, when we increased water depth for the larger species, input wave heights increased significantly with water depth (ANOVA; $P < 0 \cdot 001$; $r = 0 \cdot 7215$). Therefore, wave heights were converted to energy (eq. 1). Even though *S. filiforme* had the greatest average wave energy reduction, followed in order by *T. testudinum, Z. marina,* and *H. wrightii*, respectively, this reduction rate covaried with input wave energy; the larger *S. filiforme*, being tested in deeper water, received larger waves. Because wave energy varies roughly as the square of wave height, the same height reduction (e.g., 1 cm) of a larger wave by *S. filiforme* necessarily produced a substantially greater reduction in wave energy. Wave energy density reduction was determined as a means of accounting for

TABLE 2. Grand mean (average of replicate runs at each water depth × density combination) and standard error (SE) of wave heights (cm) entering (Ht in) and leaving (Ht out) the 1 meter test section, by seagrass species. Also, grand mean and standard error of the wave energy density reduction (over the 1 meter test section), by seagrass species. Hw = *Halodule wrightii*; Sf = *Syringodium filiforme*; Tt = *Thalassia testudinum*; Zm = *Zostera marina*. J = Joules

Species	N	Wave location	Mean		Mean reduction		
			height	SE	(J/m^2)	N	SE
Hw	33	Entering	2·4	0·14	−0·34	9	0·05
		Leaving	1·8	0·14			
Sf	24	Entering	4·9	0·33	−1·32	6	0·30
		Leaving	3·6	0·33			
Tt	24	Entering	3·6	0·18	−0·72	6	0·12
		Leaving	2·6	0·21			
Zm	41	Entering	3·7	0·12	−0·54	4	0·04
		Leaving	3·0	0·16			

TABLE 3. Summary statistics for percent wave energy reduction computed for each water depth × seagrass shoot density, by species. Grand mean (average of replicate runs at each water depth × density combination), standard error (SE), minimum, maximum, and range of the rate of percent wave energy reduction (over the 1 meter test section)

Species	N	Min.	Max.	Range	Mean	SE
Halodule wrightii	9	−21	−76	55	−44	5·93
Syringodium filiforme	6	−22	−65	43	−43	7·30
Thalassia testudinum	6	−20	−68	48	−44	8·30
Zostera marina	4	−26	−44	19	−34	3·86

this embedded difference in input wave height among species (Table 3). The percent reduction was similar for each species ($\sim 40\%$).

Percent energy reduction was utilized in a graphical representation of the data to account for the embedded relation of increasing water depth with wave height and wave energy (Figure 1). In a three-dimensional plot of percent energy reduction *vs.* water depth and density, the individual species of seagrass tend to separate showing the non-orthogonal nature of the design. In this qualitative evaluation, all species except *Z. marina* exhibited a trend of increased energy reduction with both increased density and water depth. However, only *S. filiforme*, the near-cylindrical species, showed a significant ($P < 0.05$; $n = 22$) effect on the percent energy reduction with density (Figure 2). A regression of percent energy reduction on water depth for all species combined (not shown) did not differ significantly from zero. When wave energy reduction was evaluated as a function of water depth by species (Figure 3), all species except *Z. marina* established
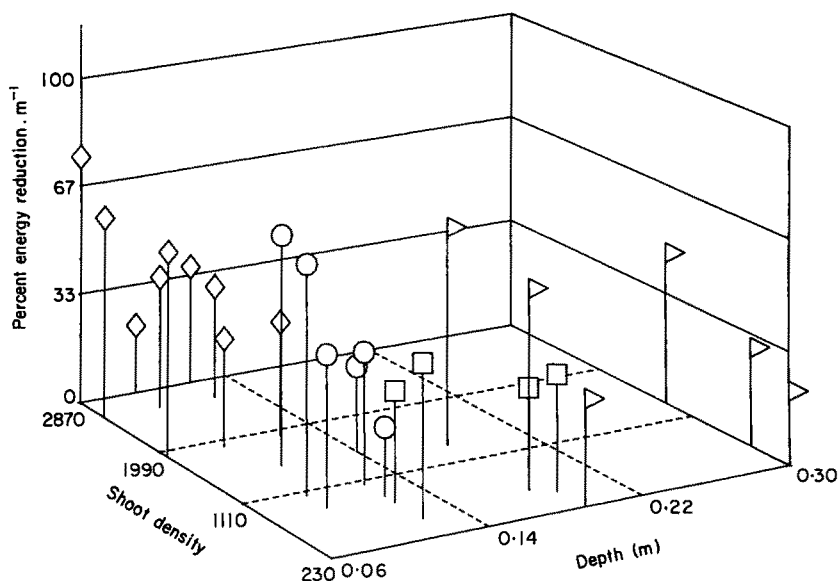
Figure 1. Average rate of percent wave energy density reduction (over the 1 meter test section) as a function of shoot density (shoots/m²) and water depth (Z) for each seagrass species. Circle = *Thalassia testudinum*, Diamond = *Halodule wrightii*, Flag = *Syringodium filiforme*, Square = *Zostera marina*.
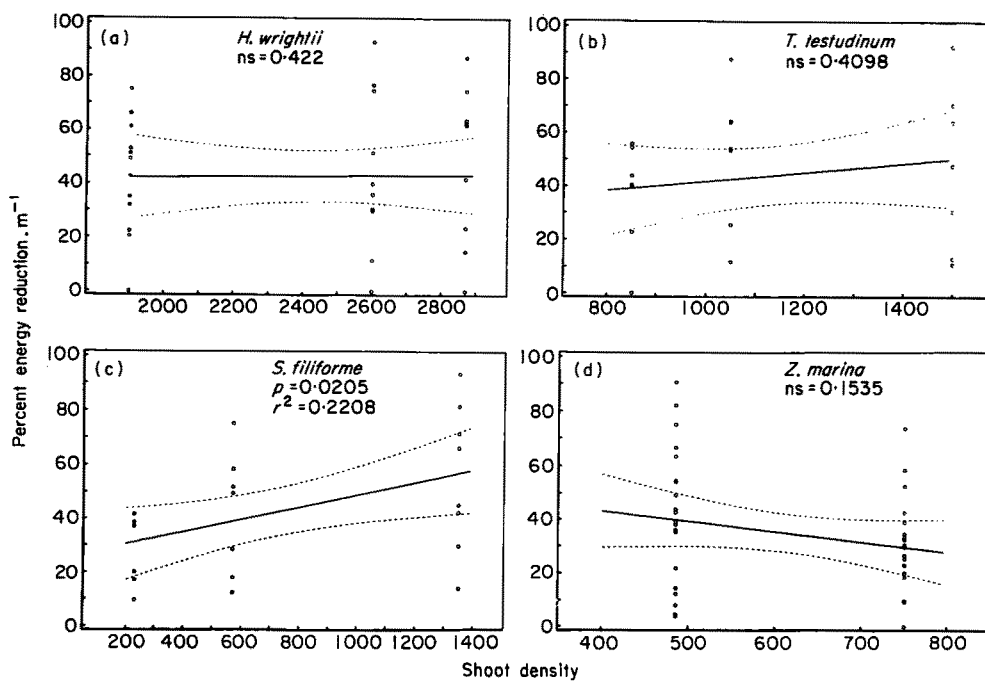

Figure 2. Regressions of rate of percent wave energy density reduction (over the 1 meter test section) by species, as a function of shoot density (shoots/m²), Confidence limits = 95%.

(a) *H. wrightii*
p = 0·0068
r^2 = 0·2132

(b) *T. testudinum*
p = 0·0033
r^2 = 0·3299

(c) *S. filiforme*
p = 0·0563
r^2 = 0·1550

(d) *Z. marina*
ns = 0·2688

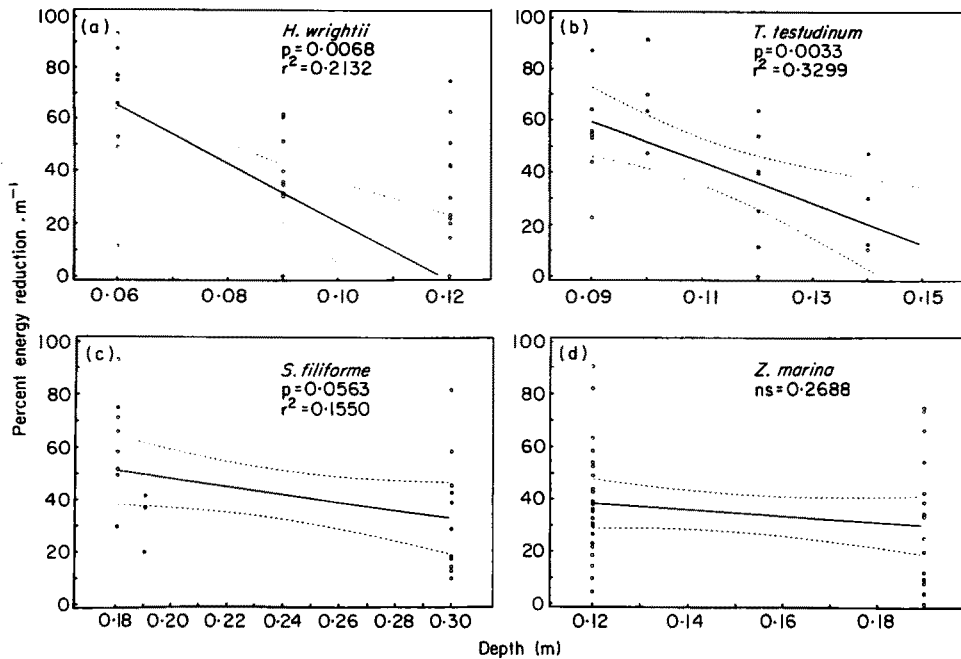Percent energy reduction . m^{-1}

Depth (m)

Figure 3. Regressions of rate of percent wave energy density reduction (over the 1 meter test section) by species, as a function of water depth (m).

significant ($P < 0.05$) regression lines. In all significant regressions, the r^2 values were low, but for *H. wrightii*, *S. filiforme*, and *T. testudinum*, the trend was for a decrease in energy reduction with increased water depth.

ANOVA was performed to test the effects of seagrass density, leaf length, and water depth on percent energy reduction (Table 4). The arcsine-transformed data exhibited a normal distribution and were homoscedastic. Leaf length alone had a highly significant effect on percent energy reduction ($P = 0.0114$, df = 1, $n = 25$) with no significant interaction effects. Due to an unanticipated smaller sample size for *Z. marina* and the poor response of wave energy reduction to change in *Z. marina* shoot density and water depth (Figures 2, 3), the analysis was repeated omitting the *Z. marina* results. The effect of leaf length on percent energy reduction was again significant while water depth became marginally significant. The interaction term of water depth and leaf length became significant. The interaction between leaf length and water depth on percent energy reduction for all species combined, excluding *Z. marina*, was plotted using SAS spline interpolation procedures (Figure 4). As water depth increased or leaf length decreased, either singly or in combination, wave energy reduction fell off quickly. This model indicates that when water depths become > = 2 times the mean leaf length, wave energy reduction became negligible when computed over a one meter horizontal distance.

Discussion

Despite different morphologies and wide ranges of densities both within and among species, a fairly consistent effect on wave energy reduction was achieved. Furthermore, the lack of shoot density effects in this study are consistent with studies of unidirectional

TABLE 4. ANOVA results for the arcsine-transformation of the rate of percent wave energy density reduction (over the 1 meter test section), as a function of shoot density, leaf length, and water depth. (A) With *Zostera marina* included, (B) with *Z. marina* deleted. ** = significant at $p < 0.05$

(a)

Source	df	Mean square	F value	P > F
Density	1	0·0548	1·94	0·1794
Depth	1	0·0687	2·44	0·1351
Leaf L.	1	0·2212	7·84	0·0114**
Density *Leaf L.	1	0·0001	0·00	0·9533
Depth *Leaf L.	1	0·0779	2·76	0·1128

(b)

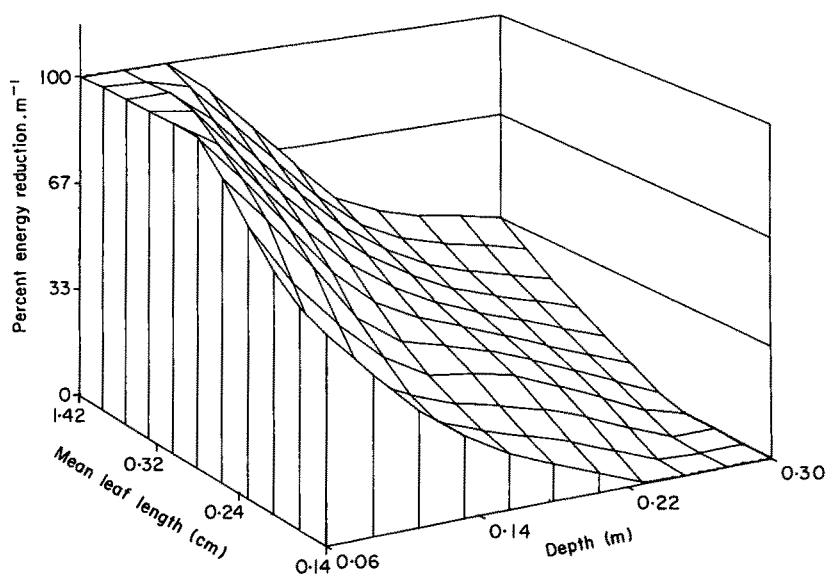| Source	df	Mean square	F value	P > F
Density	1	0·0312	1·24	0·2830
Depth	1	0·0732	2·91	0·1087
Leaf L.	1	0·2076	8·25	0·0116**
Density *Leaf L.	1	0·0010	0·04	0·8388
Depth *Leaf L.	1	0·2041	8·11	0·0122**

Figure 4. Smoothed spline interpolation of rate of percent wave energy density reduction (over the 1 meter test section) as a function of average leaf length (m) and water depth (m) for all seagrass species tested except *Zostera marina*.

flow (Fonseca *et al.*, 1982, 1983; Fonseca & Fisher, 1986; Gambi *et al.*, 1990) and may be explained using models of air flow through vegetative canopies (Cionco, 1965, 1971; Knutson *et al.*, 1982). Cionco (1965, 1971) demonstrated differences in under-canopy air flow among different crop canopies. Reduction of under-canopy air flow was attributed to flexibility as well as spacing of the canopy elements. Therefore, density of seagrass shoots does not appear to be any more influential than other potentially important factors such as plant morphology and shoot flexibility and movement in effecting flow and wave reduction. Much experimental work remains to be done on these topics in seagrass systems.

Knutson (1988) provided a detailed review of the literature on sediment accretion and modification in coastal emergent plant communities. Knutson *et al.* (1981, 1982) gave wave height and energy reduction rates with distance into beds for *Spartina* mimics and stems, respectively, based on a model by Dean (1978). Based on those data, wave energy reduction at the seaward edge of a *S. alterniflora* marsh was $7\cdot2$ J $.$ m^{-2} $.$ m^{-1}, decreasing to $1\cdot35$ J $.$ m^{-2} $.$ m^{-1}, 30 m into the marsh. The actual energy reduction rate value decreased with distance into the marsh. Wave energy reduction rate due to seagrasses in the present study is similar to levels observed 30 m into a salt marsh. There may be similar decline in the rate of wave energy dampening in seagrasses over longer distances as seen in salt marshes, however the one meter test section in the experimental flume did not allow for this observation.

The waves used by Knutson (1982) were much larger than the limited scope of this study (heights 12–23 cm *vs.* a maximum of ~ 9 cm). The percent reduction in wave energy by the saltmarsh was near 26% m^{-1} of vegetation at its seaward edge compared to the seagrass values of approximately 40% m^{-1} vegetation at the seaward edge (Table 3). In terms of wave energy reduction, the test seagrass beds had equal or greater values than the salt marsh. In Knutson's (1982) study, the plants extended above the water surface while the seagrass occupied from 50 to 100% of the water column. In this study, seagrass lost their effectiveness in reducing wave energy as the water depth increased over the canopy height. In spite of this and their smaller size and sub-surface existence, seagrasses were able, under naturally-occurring ratios of canopy height to water depth, to decrease wave energy at similar rates to salt marshes. We would expect even greater reduction when water depths were lower than the canopy height and blades lay flat on the water surface.

Morphologic differences of these seagrasses were considered to be a logical factor in a given species' ability to reduce wave energy. Streamlining and differences in flexibility may reduce the stress on the plant by reducing the plan area exposed to the flow. Kelps have been observed to elongate, or streamline, when exposed to mechanical stresses (Gerard, 1987) but this response has been shown to not be universal (Carrington, 1990). Of the seagrass species tested here, *H. wrightii* had the thinnest leaves but also showed a somewhat greater percent wave energy reduction. *Z. marina* had broader leaves and yet appeared to exhibit the lowest percent wave energy reduction. Again, this emphasizes the importance of evaluating factors such as morphology and density in concert, rather than individually and across a wide variety of wave periods and depths. Under the limited range of test conditions, it generally appeared the different seagrass species converged in function (wave energy reduction) despite an obvious disparity of form. This apparent convergence differs from the conclusion reached by Fonseca and Fisher (1986). They suggested that morphological differences among these seagrasses might be the cause of their difference unidirectional flow reduction properties and might help explain the mosaic of species distribution observed in nature as well as their associated fauna (*sensu*

Koehl, 1984; McQuaid & Branch, 1985). Expanded testing not only of wave types but the interaction of wave type with a species morphological range is needed to clarify this apparent discrepancy.

Testing the interaction of wave type and plant morphology is warranted because seagrass species appear to covary in nature with water depth (Dennison, 1979; Thayer *et al.*, 1984). Hence, species size was a prime factor in our consideration of scaling. For example, *Z. marina* has a natural range of leaf lengths from < 10 cm to over 3 m over its range in North America with larger plants being found in deeper water (pers. obs.). Most seagrass species, however, do not appear to possess the morphological variation exhibited by *Z. marina*. The potential wave heights and lengths that may be experienced by a seagrass plant extending to the water surface in 3 m of water are much larger than a smaller plant also reaching the water surface in, for example, 50 cm of water depth. The potential wave energy reduction rate under such ranges of water depth in turn becomes dependent on the size of the seagrass plants themselves. Here, we tested the seagrass canopy as it occurred naturally under the limited ranges of some local leaf length and density. As noted earlier, however, the selection of existing, natural sods imparted a non-orthogonal among-species density comparison (Figure 1). Irrespective of these specific density differences, we saw that the percent wave energy reduction was similar among all species (Table 2) with water depth/leaf length ratios being very low among all species. As water depth exceeded leaf lengths even slightly, the ability of the seagrasses to maintain a constant percent wave energy reduction in turn decreased (Figure 4), indicating that their ability to modify wave energy was being exceeded.

For all seagrass species combined, only leaf length was found to have a significant contribution to reduction in wave energy (Table 4). Because *Z. marina* was the only species which did not develop a significant relation with water depth, we experimented with removing that species from the analysis. When removed, the water depth × leaf length interaction became significant as well. We do not suggest that *Z. marina* necessarily has a different functional role in wave energy reduction, but suspect that the loss of observations for a third depth for this species and the large variability of the observed data did not allow us to detect the reduction of wave energy with water depth as exhibited by the other species. To generalize, the water depth × leaf length interaction is the more logical scenario for seagrass effects on wave energy reduction and both factors should be considered in future studies of this kind.

Loss of wave reduction effects increased as waves approached deep water status (water depth > wave length/2) when computed relative to the substrate. Even under these conditions though, much of the orbital motion under the wave would still be in contact with the canopy and resulted in a substrate-independent reduction in wave height. But in this study, if the seagrass canopy was greater than 25 cm from the water's surface, the waves would pass over the canopy and the grass would have little or no effect on the passing wave. In most cases in this study, where the water depth in the flume was less than ca. 25 cm, shallow water waves (water depth < wave length/2) were theoretically interacting not only with the canopy but the substrate. Further testing must be conducted to determine the limits of interception and absorption of energy by the canopy with a reduction of imposed stress on the substrate itself. Also, further work is required to vary wave length apart from depth to more fully understand the capacity of these plant communities to effect wave reduction, especially under circumstances where vessel-generated waves (which are apt to have a higher height/length ratio) are introduced into new areas through coastal development.

Whether mechanistic differences may or may not occur among these seagrass species, it is important to keep in mind that these species often form stands that may be meters to kilometers across. A relatively low rate of wave energy reduction by the seagrass canopy, even of deepwater waves (computed relative to the sea floor, and not the canopy) becomes dramatic when applied over long distances. For example, under the conditions we tested, where the plants approach the water surface, waves of the size tested would have been completely attenuated within 4–7 meters, depending on the seagrass species. In open water situations, such as the west coast of Florida or Pamlico Sound, North Carolina, two areas with substantial fetches leading to broad (tens of kilometers), sometimes deeper water (2–10 m) seagrass beds, a much greater over-bed distance would be required to measurably effect the larger, longer period waves, as suggested by Wayne (1975). This reduction would eventually be enhanced in shallow water seagrass beds by the influence of the shoal itself. There, deepwater waves would become shallow water waves and at some point exceed the capacity of the canopy to attenuate wave energy and experience bottom friction beyond that imparted by the seagrass alone. Patchy, dune-like formations of seagrass beds may also require separate consideration to account for the interaction of the raised seagrass patches embedded in an irregular bathymetry and this effect on passing waves.

Much work remains to be done to evaluate not only the role of seagrasses in wave reduction, but the converse effect of waves on seagrass ecosystems. Most studies of seagrass ecosystems have been concerned only with unidirectional flow-related interactions of the seagrass canopy, where such phenomena have been mentioned at all. The limited data presented here demonstrate the capacity of different seagrass species to significantly reduce wave energy ($\sim 40\%$) when occupying most of the water column and by extension, enhance sediment stability. This reduction capability compares favorably with saltmarsh wave reduction capabilities. Model development incorporating different wave characteristics, water depths, and seagrass morphometrics may provide clarification of the functional attributes of seagrass ecosystems across gradients of wave exposure in the nearshore environment.

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