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CONTENTS

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Impact of Boat-Generated Waves on a Seagrass Habitat

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ABSTRACT

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Although previous studies proved that boats can have a negative impact on seagrasses when their anchors and/or rotating props are in direct contact with the plants, very little is known about the indirect impacts (*e.g.*, hydrocarbon emissions, oil leaks, and waves) that boats can have on seagrasses. This study quantified the impact of boat-generated waves on a *Ruppia maritima* habitat in Chesapeake Bay. During a calm and clear day, a V-hulled boat was driven at two speeds through a study site in the bay at high and low tide. Waves, suspended solids, nutrients and light levels were monitored before, during, and after the boat runs. The possible negative impacts (increased sediment resuspension, release of sediment nutrients, and reduced light levels) were much smaller than expected, being minimal when compared to natural fluctuations in this habitat (conditions to which the plants have acclimated). The strongest impact was observed at low tide when boat-generated waves resuspended a small amount of sediment, which was redeposited within minutes. Boat-generated waves apparently also caused porewater pumping, which increased the concentration of ammonia in the water column. This has the potential to contribute to eutrophication and, over long periods of time, to have a negative impact on seagrass beds. High boat speeds at high tide seem to minimize detrimental conditions in seagrass habitats. In contrast, stormy and cloudy days as well as dusk and dawn, when light availability is reduced, are the most vulnerable conditions for seagrasses. Fortunately, recreational boating activity is usually reduced under these conditions.

ADDITIONAL INDEX WORDS: *Speed, tide, nutrients, suspended solids, light, eutrophication, barges, porewater pumping, grain size, trapping.*

INTRODUCTION

Coastal development is not only impacting the land but also adjacent estuarine, coastal, and marine waters. Accelerated eutrophication of coastal waters has been linked to an increase in the number of households (SHORT *et al.*, 1996). Additionally, coastal development is leading to an increase in the number of recreational vessels (jet skis, sail boats, and motorboats) that navigate in shallow areas (CLARK, 1995; KRUER, 1998). This can lead to a conflict between boaters and the natural resources found in these shallow waters.

Seagrass beds are considered one of the most valuable coastal resources due to the many ecological services they perform (COSTANZA *et al.*, 1997). The distribution of these plants depends on light availability (DENNISON *et al.*, 1993; SHORT and WYLLIE-ECHEVERRIA, 1996). Consequently, seagrasses are found in the shallow waters often shared with boaters. Boats equipped with propellers (in contrast to water jets) have been shown to cause direct damage to seagrasses when the prop comes in contact with the plants and the sediment, resulting in narrow dredged channels (prop scars) through the vegetation (ZIEMAN, 1976; CLARK, 1995; DAWES *et al.*, 1997). Depending on the species, these 'prop scars' in seagrass beds take many years to recover (WILLIAMS, 1988; DAWES *et al.*, 1997; MEEHAN and WEST, 2000). The same applies to scars in seagrass beds caused by anchors (WILLIAMS, 1988; CREED and AMADO-FILHO, 1999; FRANCOUR *et al.*, 1999) and boat moorings (WALKER *et al.*, 1989). There is no doubt that, when boats come in direct contact with seagrasses, damage is likely to occur. In contrast, the indirect impact of boats on seagrasses is poorly understood.

Based mostly on intuition, it is believed that boating activity resuspends sediments and, therefore, reduces light availability in coastal waters (CRAWFORD, 1998; HARTGE, 1998; KRUER, 1998). As seagrasses need light in order to survive, boating could have an indirect impact on seagrasses via increased suspended matter and elevated nu-

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trient concentrations. In the long-term, such increases could lead to their decimation (KRUER, 1998). This study analyzes the magnitude of the indirect impact of boat-generated waves on a seagrass habitat in Chesapeake Bay.

METHODS

A day with a gentle breeze (according to the Beaufort wind scale) and clear skies was chosen in the summer of 2000 (August 25) to minimize wind-generated waves and to maximize light availability, respectively. On that day, a 21 foot (6.9 m) V-hulled boat (Wetzig) was taken to Hopkins Cove at the mouth of the Honga River in Chesapeake Bay (Figure 1). This cove is partially vegetated by *Ruppia maritima*, while the remaining portion of the cove is unvegetated. The reason for the lack of vegetation in a portion of the cove is not clear. The boat was used to generate waves for a period of 15 minutes at two speeds: 6.4 knots (11.8 kmph) and 14.9 knots (27.6 kmph) at both high and low tide. The boat was driven in large circles such that it always passed the cove at the 1.5 m depth contour moving from NW to SE (Figure 1). At high speed, the boat was in a plane but not at the lower speed. Therefore, at low speed and low water, the prop touched the sediment surface and generated a direct impact. Since prop scarring was not the focus of this study, the low speed/low tide treatment was dropped from the experimental design. Wind data were obtained from the Chesapeake Bay Observing System (www.cbos.org) mid-bay buoy located at 38°28.4′N, 76°22.8′W, approximately 40 km northwest of the study site.

A series of environmental parameters was quantified from 1 hour prior to the first boat run to 3 hours after the last boat run at poles positioned at the 1 m depth contour (high tide) in the vegetated and unvegetated areas of the cove. The wave characteristics (height and period) were quantified using a pressure gauge (Macrowave, Coastal Leasing, Cambridge, MA, USA), which recorded water height at a 5 Hz frequency for 10 minutes (4096 points), every 15 minutes. These data were later Fast-Fourier analyzed using the PC Spec Program from Coastal Leasing to obtain significant wave height (H) and wave period (P). Wave frequency (F) was calculated as $F = 1/P$. Since water depth at the sampling poles was shallower than half the wavelength (L) (deep water waves) and deeper than L/20 (shallow water waves), L was calculated based on the equation for transitional waves (intermediate to shallow and deep water waves):

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{L'}\right)$$

where g is the acceleration of gravity, d the water depth, and L′ the estimated wavelength (average of $L_{shallow}$ and L_{deep}).

Light availability was quantified by deploying a spherical underwater quantum sensor (LI-COR 193SA, Lincoln, NE, USA) 20 cm above the sediment surface at the unvegetated site, which avoids the confounding effect of light attenuation by the vegetation. A data logger (LI-COR 1000) recorded light levels every minute and averaged them for every 5 minutes. Water samples (1 liter) were collected at both the vegetated and unvegetated sites (20 cm above the bottom) every 10 minutes using automated water samplers (ISCO Model 3700, Lincoln, NE, USA). In the laboratory, three 300 ml sub-samples were filtered through GF/F filters to obtain the total suspended solid (TSS) concentration of each sample. These filters were then ashed (450°C for 4 hours) to obtain the fraction of particulate organic matter (POM). Nutrient samples (ammonia, nitrate + nitrite, and orthophosphate) for selected periods immediately before, during, and after the boat runs were obtained from the filterate of the water samples. These samples were then analyzed according to WHITLEDGE *et al.* (1981) using an auto analyzer (Technicon II).

Surface (top 5 cm) sediment samples ($n = 10$) were randomly collected in the vegetated and unvegetated areas of Hopkins Cove using a core (8 cm in diameter). These samples were then analyzed for percent organic content (combustion at 450°C for 4 hours) and percent silt and clay (wet sieving through a 63 μm sieve). The seagrasses were characterized by measuring their density (shoot counts in three 25 × 25 cm quadrats every 5 m along a 570 m transect parallel to the shoreline). Seagrass light requirements were based on photosynthesis × irradiance (PI) curves obtained from oxygen evolution measurements. Three mid-aged *Ruppia* leaf segments (3 cm long) were placed in a Hansatech system (Norfolk, England), where they were immersed in natural seawater and exposed to a range of light intensities (including darkness). The photosynthetic rate was measured when steady state at each light level was reached. These data were then used to plot PI curves from which the saturation light intensity was obtained by applying the curve fitting function in

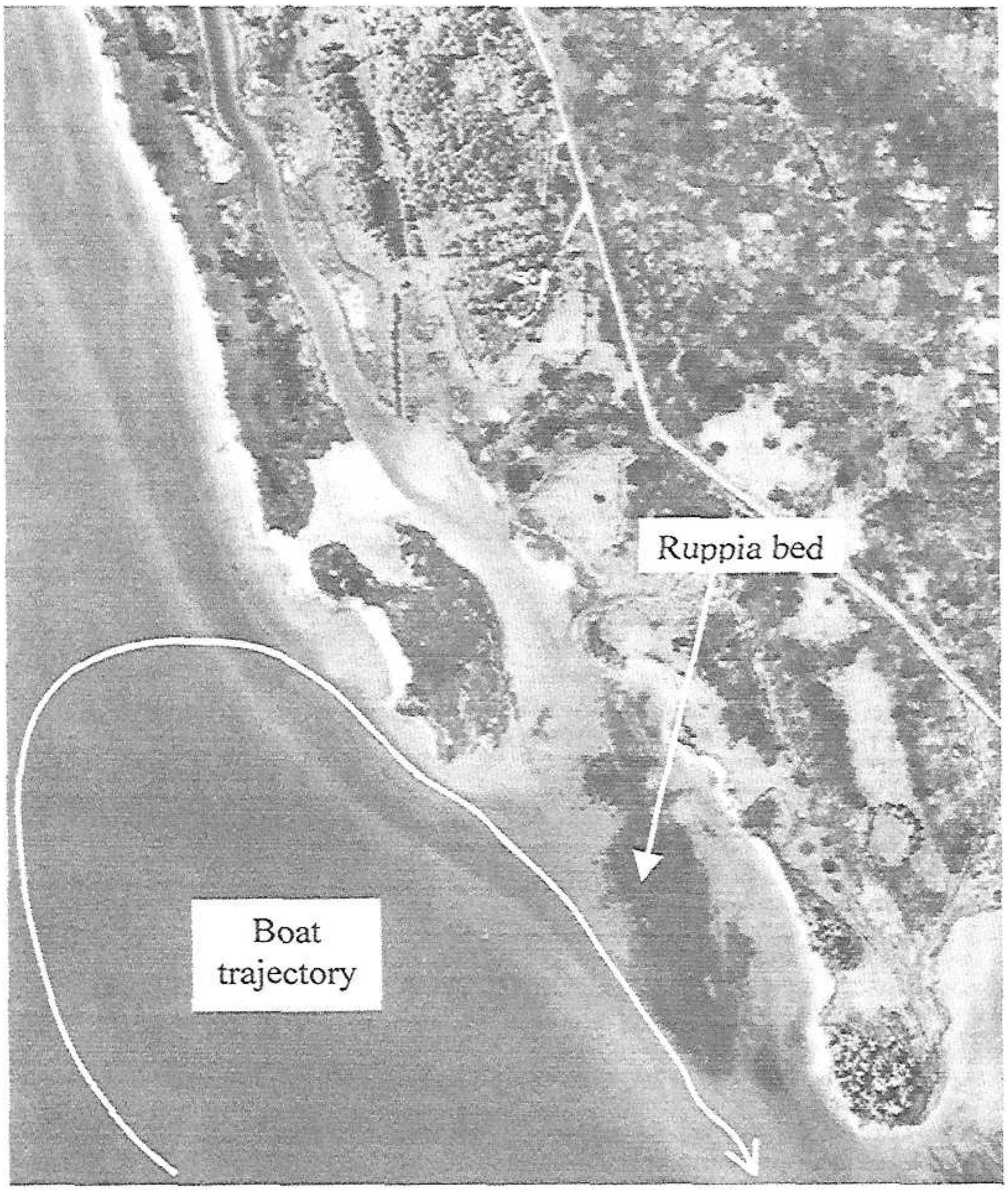

Figure 1. Study site at Hopkins Cove in Chesapeake Bay. White line indicates the boat trajectory during the different runs.

KaleidaGraph (Sydney Software, Reading, PA, USA). Where applicable, statistical analysis of the data was performed via regressions and ANOVA. The data were tested for normality and homogeneity of variance and log transformed when necessary.

RESULTS

The northern part of Hopkins Cove was unvegetated, while the southern portion was colonized by *Ruppia maritima* at an average (± SD) density of 772 ± 705 shoots m^{-2}. The light level at which

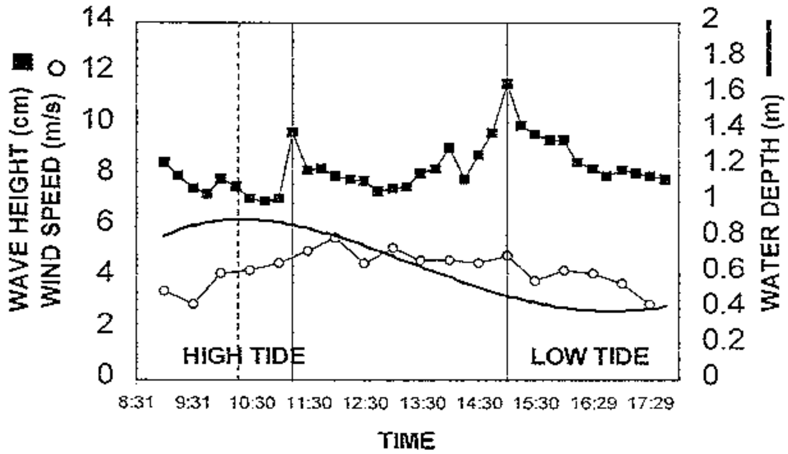

Figure 2. Time series of wind speed (open circles), water depth (solid line), and wave height (solid squares) during the experiment on 25 August 2000. Vertical lines indicate the time of initiation of the slow speed (dashed line) and high speed (solid lines) boat runs.

photosynthesis of *Ruppia* saturated was 48.86 ± 45.82 μmol photons m^{-2} s^{-1} (± SD). While there was a significantly higher (F = 9.05; P = 0.0076) amount of fine particles in the sediment in the unvegetated (30.14 ± 19.13%) than in the vegetated (11.68 ± 3.30%) area, there was no significant difference in organic content in these two areas (1.31 ± 0.55% and 0.95 ± 0.21%, respectively).

The wind intensity during the study period was relatively calm (3.0 to 5.6 m s^{-1}) (Figure 2) and came from the N and NE directions from which the study site is protected by land. In the morning, winds were from the N and slowly increased from 3.0 to 5.6 m s^{-1}. Winds remained from the N until 17:00 when they switched to the NE. In the afternoon, the winds decreased from the maximum of 5.6 m s^{-1} (noon) to 3.0 m s^{-1} at 17:30. The tide was highest at 10:30 (0.9 m at the sampling poles) and lowest at 16:30 (0.4 m at the sampling poles) (Figure 2). The boat runs took place at 10:15 (low speed), 11:15 am (high speed), and 15:00 (high speed).

Some of the boat-generated waves clearly differed from the ambient waves (Figure 2). While waves generated at low boat speed did not cause a notable increase in wave height, waves generated at high boat speed were between 1.75 and 2.05 cm higher (low and high tides, respectively) than the waves observed just prior to and after the boating activity (Figure 2). The frequency of the boat-generated waves increased from 0.39 to 0.51 Hz when the boat was moving at slow speed. In contrast, at high speed, the frequency of boat-generated waves was indistinguishable from the remaining wave record (between 0.35 and 0.43 Hz). Wavelengths tended to fluctuate between 0.46 and 6.19 m in the morning. In contrast, wavelengths steadily declined from 5.20 to 3.10 m in the afternoon (Figure 3).

The overall levels of total suspended solids (TSS) were higher in the unvegetated area than in the vegetated area, but this difference was only significant in the morning (F = 16.16, P = 0.0001). The dominant feature in the TSS time-series was the peak (up to 72 mg l^{-1}) in the afternoon hours which was not linked to any boating activity purposely generated in the study (Figure 4) but to the wavelength of the waves observed in the afternoon hours (Figure 3). Boating activity had only a minor impact on TSS levels in the vegetated area. In contrast, in the unvegetated area, TSS levels at 20 cm above the sediment were usually reduced by the boating activity. Only at high speed and low tide was an increase in TSS observed in the unvegetated (5.66 mg l^{-1}) and vegetated (5.85 mg l^{-1}) areas. The POM fraction was significantly lower in the vegetated than in the unvegetated area (F = 20.22, P = 0.00001) and was significantly lower in the morning than in the afternoon in both vegetated (F = 148.80) and unvegetated (F = 254.68) areas. Additionally, POM was a linear and positive function of TSS in the vegetated (R^2 = 0.8895) and

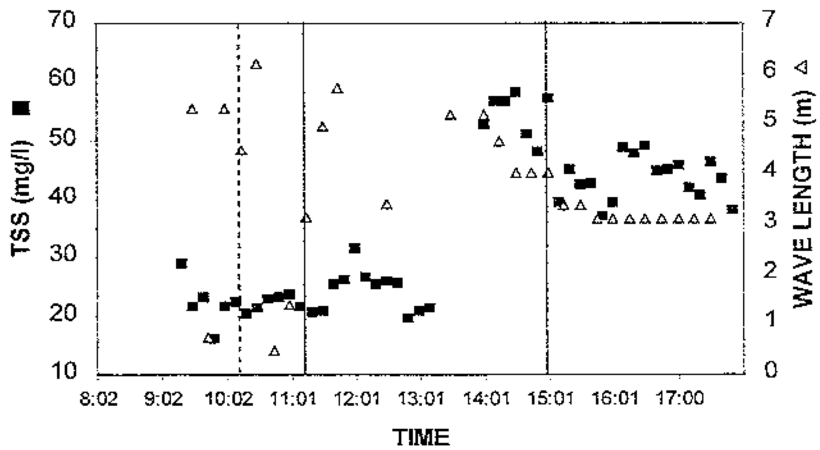

Figure 3. Time series of total suspended solids (TSS) in the unvegetated area (solid boxes) and wavelength (open triangles) at the study site. The missing points between 13:30 and 14:00 represent the time required to change the bottles in the automated water samplers. Vertical lines indicate the time of initiation of the slow speed (dashed line) and high speed (solid lines) boat runs.

unvegetated ($R^2 = 0.8493$) areas. Boating activity only had a minor impact on POM. In the vegetated area, it only increased (<1%) after the first boat run (low speed/high tide), while in the unvegetated area it only increased (also <1%) after the last run (high speed/low tide).

Nutrient concentrations in the water column differed between the vegetated and unvegetated areas, just 160 m apart. Ammonia concentrations were significantly higher in the unvegetated than in the vegetated area ($F = 5.39$; $P = 0.0299$). The opposite was true for orthophosphate ($F = 5.43$; $P = 0.0293$). Additionally, ammonia concentrations tended to increase with increasing wave height in both the vegetated ($R^2 = 0.5837$; $F = 14.02$; $P = 0.0038$) and unvegetated ($R^2 = 0.3156$; $F = 4.61$; $P = 0.057$) areas. The impact of boating activity on nutrient levels was minimal when compared to natural fluctuations. Ammonia levels increased slightly after the high speed boat run at low tide (vegetated and unvegetated) but, in a matter of minutes, returned to ambient levels (Figure 4). Phosphorus levels also increased (0.02 μM) after the slow boating event at high tide (vegetated and unvegetated).

Due to the lack of light data above the water surface, it is unclear if the fluctuations in the light observed in Figure 5 are due to the passage of isolated clouds or due to changes in the water quality. Assuming that the decrease in light levels during the boating activity is due to a change in the seagrass habitat and not cloud cover, the low speed boat run at high tide would have decreased light in 230 μmol photons $m^{-2} s^{-1}$, while the high speed boat run at high tide would have decreased light in 450 μmol photons $m^{-2} s^{-1}$ (Figure 5). No change in light availability was observed after the high speed boat run at low tide, an indication that our assumption is wrong and that cloud cover indeed affected the light levels in the previous treatments.

DISCUSSION

General Trends

The study site was unique in that the amount of fine particles in the unvegetated area was higher than in the vegetated area. The opposite is usually expected as seagrasses effectively reduce currents and waves promoting sediment deposition (FONSECA, 1996). Perhaps the wave-dominated nature of this habitat does not allow for the hydrodynamically calm conditions that are needed to increase particle deposition (KOCH and GUST, 1999). This implies that not all seagrass beds trap sediment particles at the same rate (KOCH, 1999) and may even contribute to particle resuspension.

The TSS levels in both the vegetated and unvegetated areas were always higher than 15 mg l^{-1},

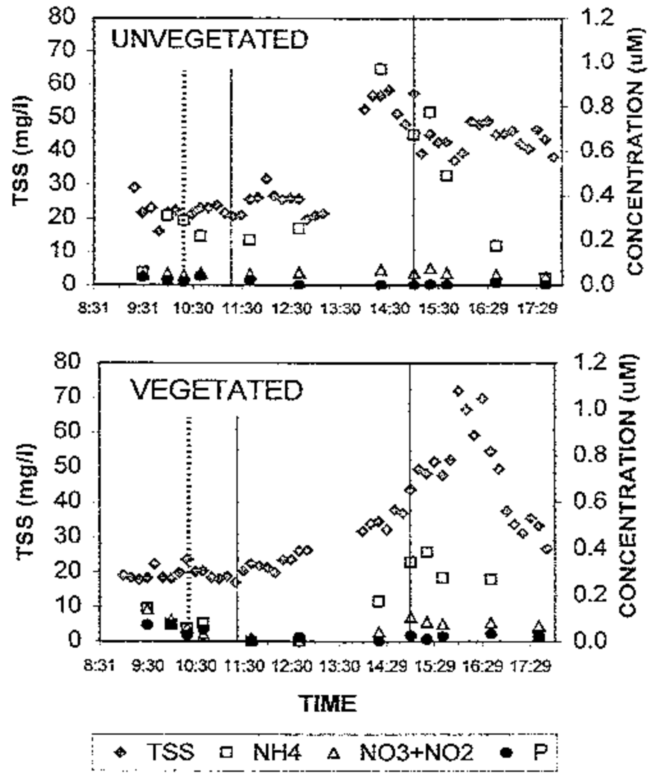

Figure 4. Time series of total suspended solids and nutrient concentrations recorded in the vegetated and unvegetated areas at the study site. The missing points between 13:30 and 14:00 represent the time required to change the bottles in the automated water samplers. Vertical lines indicate the time of initiation of the slow speed (dashed line) and high speed (solid lines) boat runs.

the suggested upper limit for seagrass existence in Chesapeake Bay (DENNISON *et al.*, 1993). Even so, the plants in this area were healthy. Therefore, this limit may need to be revised. Resuspension of sediments is usually higher in unvegetated than in vegetated areas (WARD *et al.*, 1984), especially when the sediments in the unvegetated area are finer than in the vegetated area (FONSECA, 1996), as was the case in this study. Data reported here confirm this trend. Additionally, these data show a close relationship between afternoon TSS levels and wavelength. Long (low frequency) waves penetrate the water column deeper than short (high frequency) waves (BROWN *et al.*, 1991) and, as a result, may be responsible for the peak in TSS concentration. Resuspension (unrelated to boating activity) apparently occurred first in the unvegetated area after which the water mass was slowly advected into the vegetated area by the ebb currents at approximately 2 cm s^{-1} (see delay in TSS peaks between unvegetated and vegetated areas in Figure 4). These long waves observed in the afternoon hours can not be explained by the wind pattern, but may have been generated by the passage of barges in the Chesapeake Bay Channel (17 km west of the site), which were observed in the afternoon but not in the morning. The indirect impact of barges navigating offshore of seagrass beds remains to be investigated.

The lower POM levels in the vegetated versus the unvegetated area could be explained by the lower nutrient availability within the vegetation. If nutrient levels are low, growth of phytoplankton and microphytobenthos (MPB) is reduced (SHORT and SHORT, 1984). The strong correlation between TSS and POM and the link between TSS and wavelength suggest that resuspended MPB may have been an important component of the POM

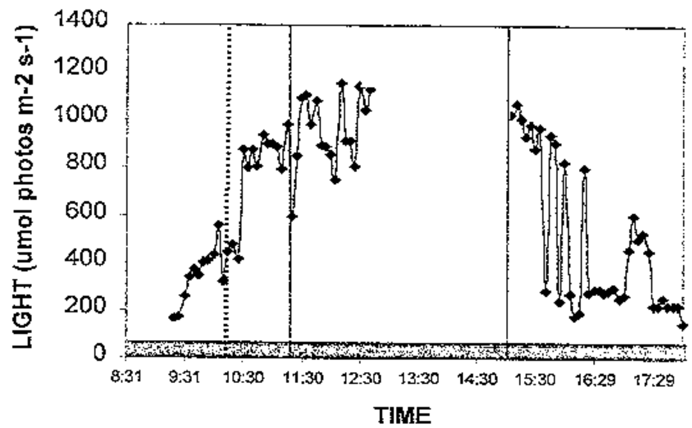

Figure 5. Light levels at 20 cm from the bottom in the unvegetated area during the exposure of the study site to different boat-generated wave heights. Vertical lines indicate the time of initiation of the slow speed (dashed line) and high speed (solid lines) boat runs. Grey horizontal box indicates the light levels at which photosynthesis of *Ruppia maritima* blade segments (not entire plants) is below saturation. The gap in the data set represents a period during which the platform was shading the light sensor.

fraction. It is unlikely that the POM originated from phytoplankton growth.

The link between ammonia concentration and wave height in both vegetated and unvegetated areas could be explained by porewater pumping. In this process, the differential hydrostatic pressure of wave peaks and troughs exerted by the passage of the waves on the sediment surface (CARSTENS, 1968; STEELE *et al.,* 1970) leads to the release of porewater (especially ammonia) from the sediments into the water column (WEBB and THEODOR, 1968, 1972; STEELE *et al.,* 1970).

The Impact of Boat-Generated Waves

At high tide, the impact of boating activity on the seagrass habitat was minimal. At low speed, the high frequency waves generated by the boat, possibly a result of propeller motion and/or boat wake (CRAWFORD, 1998), tended to dissipate without causing sediment resuspension. In the unvegetated area, TSS levels actually dropped following the passage of the boat. This could be due to the mixing of the water column (without sediment resuspension) bringing less turbid water from the surface to the bottom where the samples were collected. Mixing of the water column results in no net change in water clarity. As a result, there should be no change in light availability to the benthic vegetation. The decrease in light level observed during the low speed run at high tide, therefore, was probably due to the passage of a cloud and not to attenuation of light in the water column.

The impact of high speed boat runs, when the waves were clearly higher (but at the same frequency) than ambient waves, was a function of tidal height. At high tide, TSS concentrations near the bottom were lowered, once again suggesting mixing of the water column without sediment resuspension. In contrast, at low tide, a small increase in TSS and POM was observed after the passage of the boat suggesting resuspension of sediment and microphytobenthos. This could be explained by the relatively long waves (deep penetration into the water column) and the increased wave height. The erosional capacity of waves increases with wave height (HAMILTON and MITCHELL, 1996; BAILEY and HAMILTON, 1997). The TSS and POM levels were not impacted by boating activity during high tide, once again emphasizing the importance of water depth when evaluating the indirect impact of boats. The short-lived ammonia pulse observed in the vegetated and unvegetated areas after the boat run at low tide parallels the findings of increased TSS levels after this treatment (*i.e.,* the boat-induced increase in wave height could have resulted in porewater pumping).

In the vegetated area, the small increase in TSS observed after the passage of the boat at low speed/high tide (first run) and high speed/low tide

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(last run) could be due to the dislodgement of particles that had previously settled onto the seagrass leaves. As observed for other sites (CRAWFORD, 1998), just minutes after the boat run, the TSS levels in the vegetated area returned to ambient levels. Perhaps this increase in TSS was not observed after the high speed/high tide run because only a small amount of particles had settled onto the leaves in one hour (time since the low speed/high tide run). Similarly, POM only increased in the water column after the first boat run, again suggesting that this material was released from the leaves (epiphytic algae) and was unavailable for resuspension during the last few hours until the experiment was terminated. No epiphyte data were collected during this study to confirm this hypothesis. Should it prove to be true, boating activity at high tide may be potentially beneficial to seagrasses by reducing the epiphytic cover on seagrass leaves.

The light reductions recorded during the morning boat runs appear to be due to the passage of isolated clouds and not to a change in water quality. Therefore, the impact of boat-generated waves on light availability (via sediment resuspension) was minimal. If a reduction in light availability would have been recorded, it would have affected the seagrasses colonizing the deepest areas (DENNISON *et al.*, 1993), as well as all seagrasses (shallow and deep) during the morning hours (ZIMMERMAN *et al.*, 1994) or on cloudy days when the incident light levels are closer to the saturation level. Boating activity is usually reduced during these times and maximum during sunny calm days when incident light levels are high and naturally occurring TSS levels are low.

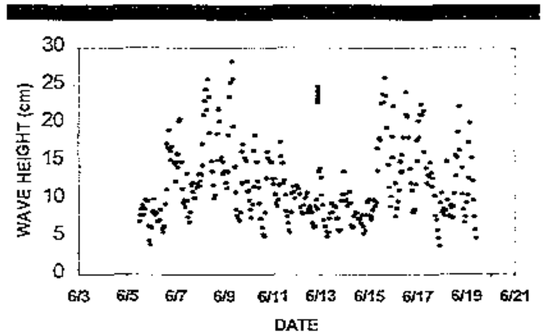

Figure 6. Wave height in the unvegetated area of the study site during a 14-day period prior to the boating experiment. Note the two storm events on June 8 and 15–16, 2000. For comparison purposes, the wave height of the boat-generated waves is represented by the solid vertical line.

SUMMARY AND CONCLUSIONS

The 'universal' belief that seagrass beds are efficient sediment traps was questioned in this study since the percentage of fine particles in the sediments was higher outside the vegetation than in the seagrass bed. In contrast, this study also confirmed well-established concepts of sediment resuspension and nutrient availability in seagrass habitats. Sediment resuspension was higher in the unvegetated than in the vegetated area and was highest when wave period was longest over extended periods of time (possibly generated by barges). Additionally, nutrient levels were lower in the vegetated than in the unvegetated area, and the concentration of ammonia was a function of wave height suggesting porewater pumping in both vegetated and unvegetated areas.

The negative impact of boat-generated waves on seagrass habitat quality was minimal. Boat-generated waves were very small when compared to naturally occurring waves at the study site (Figure 6), and, as a result, the impact of the boat runs was also much smaller than natural fluctuations to which the local seagrasses had acclimated. The strongest impact was observed at low tide (0.4 m water depth) when boat-generated waves resuspended a small fraction of TSS, which was redeposited in a few minutes resulting in little or no impact on the light availability. In the vegetated area, the boat-generated waves apparently caused epiphytes and particulate matter to be dislodged from the leaves (a positive effect), but more data are needed to confirm this hypothesis.

Over long periods of time, the porewater pumping (ammonia release) resulting from increased wave height (boat-generated) has the potential to contribute to eutrophication and could have a negative impact on seagrass beds. However, in general, the impact of boat-generated waves on this seagrass habitat was much smaller than expected. It appears that navigating at high speed and at high tide between 10 am and 5 pm is the best way to minimize the indirect impact of boating activity on seagrass habitats. Barge-generated waves may have a larger negative impact on seagrass habitats, but this still needs to be investigated.

LITERATURE CITED

BAILEY, M.C. and HAMILTON, D.P., 1997. Wind induced sediment resuspension: a lake-wide model. *Ecological Modeling*, 99, 217–228.

BROWN, J.; COLLING, A.; PARK, D.; PHILLIPS, J.; ROTHERY, D., and WRIGHT, J., 1991. *Waves, Tides and Shallow-Water Processes.* Pergamon Press, Open University, Milton Keynes, England, pp. 8–29.

CARSTENS, T., 1968. Wave forces on boundaries and submersed bodies. *Sarsia,* 34, 37–60.

CLARK, P.A., 1995. Evaluation and management of propeller damage to seagrass beds in Tampa Bay, Florida. *Florida Scientist,* 58, 193–196.

COSTANZA, R.; D'ARGE, R.; DE GROOT, R.; FARBER, S.; GRASSO, M.; HANNON, B.; LIMBURG, K.; NAEEM, S.; O'NEIL, R.V.; PARUELO, J.; RASKIN, R.G.; SUTTON, P., and VAN DEN BELT, M. 1997. The value of the world's ecosystem services and natural capital. *Nature,* 387, 253–260.

CRAWFORD, R.E., 1998. Measuring boating effects on turbidity in a shallow coastal lagoon. *In:* CRAWFORD, R.E.; STOLPE, N.E., and MOORE, M.J. (eds.). *The Environmental Impacts of Boating; Proceedings of a Workshop Held at Woods Hole Oceanographic Institution.* Woods Hole, MA, USA, December 1994, WHOI-98-03 Technical Report.

CREED, J.C. and AMADO-FILHO, G.M., 1999. Disturbance and recovery of the macroflora of a seagrass (*Halodule wrigthii*) meadow in the Abrolhos Marine National Park, Brazil: an experimental evaluation of anchor damage. *Journal of Experimental Marine Biology and Ecology,* 235, 285–306.

DAWES, C.J.; ANDORFER, J.; ROSE, C.; URANOWSKI, C., and EHRINGER, N., 1997. Regrowth of the seagrass *Thalassia testudinum* into propeller scars. *Aquatic Botany,* 59, 139–155.

DENNISON, W.C.; ORTH, R.J.; MOORE, K.A.; STEVENSON, J.C.; CARTER, V.; KOLLAR, S.; BERGSTROM, P.W., and BATIUK, R.A., 1993. Assessing water quality with submersed aquatic vegetation. *BioScience,* 43, 86–94.

FONSECA, M.S., 1996. The role of seagrasses in nearshore sedimentary processes: a review. *In:* NORDSTROM, K.F. and ROMAN, C.J. (eds.), *Estuarine Shores: Evolution, Environments and Human Alterations.* New York: John Wiley & Sons, pp. 261–286.

FRANCOUR, P.; GANTEAUME, A., and POULAIN, M., 1999. Effects of boat anchoring in *Posidonia oceanica* seagrass beds in the Port-Cros National Park. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 9, 391–400.

HAMILTON, D.P. and MITCHELL, S.F., 1996. An empirical model for sediment resuspension in shallow lakes. *Hydrobiologia,* 317, 209–220.

HARTGE, P., 1998. Boat-induced turbidity. *In:* CRAWFORD, R.E.; STOLPE, N.E., and MOORE, M.J. (eds), *The Environmental Impacts of Boating; Proceedings of a Workshop Held at Woods Hole Oceanographic Institution.* Woods Hole, MA, USA, December 1994, WHOI-98-03 Technical Report.

KOCH, E.W., 1999. Sediment resuspension in a shallow *Thalassia testudinum* bed. *Aquatic Botany,* 65, 269–280.

KOCH, E.W. and GUST, G., 1999. Water flow in tide and wave dominated beds of the seagrass *Thalassia testudinum. Marine Ecology Progress Series,* 184, 63–72.

KRUER, C., 1998. Boating impacts on seagrass habitat in Florida. *In:* CRAWFORD, R.E.; STOLPE, N.E., and MOORE, M.J. (eds.), *The Environmental Impacts of Boating; Proceedings of a Workshop Held at Woods Hole Oceanographic Institution.* Woods Hole, MA, USA, December 1994, WHOI-98-03 Technical Report.

MEEHAN, A.J. and WEST, R.J., 2000. Recovery times for a damaged *Posidonia australis* bed in southeastern Australia. *Aquatic Botany,* 67, 161–167.

SHORT, F.T. and SHORT, C.A., 1984. The seagrass filter: purification of estuarine and coastal waters. *In:* KENNEDY, V.S. (ed.), *The Estuary as a Filter.* New York: Academic Press, pp. 395–413.

SHORT, F.T.; BURDICK, D.M.; GRANGER, S., and NIXON, S.W., 1996. Long-term decline in eelgrass, *Zostera marina* L., linked to increased housing development. *In:* KUO, J.; PHILLIPS, R.C.; WALKER, D.I., and KIRKMAN, H. (eds.), *Seagrass Biology—Proceedings of an International Workshop.* Western Australia Museum, Perth, Australia, pp. 291–298.

SHORT, F.T. and WYLLIE-ECHEVERRIA, S., 1996. Natural and human-induced disturbance of seagrasses. *Environmental Conservation,* 23, 17–27.

STEELE, J.H.; MUNRO, A.L.S., and GIESE, G.S., 1970. Environmental factors controlling the epipsamic flora on beach and sublittoral sands. *Journal of the Marine Biological Association of the United Kingdom,* 50, 907–918.

WALKER, D.I.; LUKATELICH, R.J.; BASTYAN, G., and MCCOMB, A.J., 1989. Effect of boat moorings on seagrass beds near Perth, Western Australia. *Aquatic Botany,* 36, 69–77.

WARD, L.; KEMP, W.M., and BOYNTON, W.R., 1984. The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. *Marine Geology,* 59, 85–103.

WEBB, J.E. and THEODOR, J., 1968. Irrigation of submerged marine sands through wave action. *Nature,* 220, 682–683.

WEBB, J.E. and THEODOR, J., 1972. Wave-induced circulation in submerged sands. *Journal of the Marine Biological Association of the United Kingdom,* 52, 903–914.

WHITLEDGE, T.C.; MALLORY, S.C.; PATTON, C.J., and WIRICK, C.D., 1981. *Automated Nutrient Analysis in Seawater.* Department of Energy and Environment, Brookhaven National Laboratory, Upton, NY. BNL#51398.

WILLIAMS, S.L., 1988. *Thalassia testudinum* productivity and grazing by green turtles in a highly disturbed seagrass bed. *Marine Biology,* 98, 447–455.

ZIEMAN, J.C., 1976. The ecological effects of physical damage from motor boats on turtle grass beds in southern Florida. *Aquatic Botany,* 2, 127–139.

ZIMMERMAN, R.C.; CABELLO-PASINI, A., and ALBERTE, R.S., 1994. Modeling daily production of aquatic macrophytes from irradiance measurements: a comparative analysis. *Marine Ecology Progress Series,* 114, 185–196.