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Toward a Sustainable Coastal Watershed:
The Chesapeake Experiment. Proceedings of a Conference
1-3 June 1994. Norfolk, VA
Chesapeake Research Consortium Publication No. 149

Short- and Long-Term Light Effects of Sediment Processes

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Abstract: Microbial, benthic heterotrophic processes that direct exchanges of material between sediments and overlying water tend to degrade water quality by taking up oxygen and releasing inorganic nutrients. Within shallow sediments the potential exists for photoautotrophy and amelioration of water quality degradation. We investigated light effects on the exchange of oxygen, carbon dioxide, ammonium, nitrate plus nitrite, and filterable reactive phosphorus between shallow (1 m and 2 m depths) sediments and the water column at four National Estuarine Research Reserves. Two were in the York River, Virginia, and two were in North Carolina. Short-term light effects were evaluated for different irradiance conditions during incubation; long-term effects were inferred from results by sediments from different depths.

Short-term responses to light were consistently evident for oxygen, carbon dioxide, and ammonium exchanges when sediments were predominantly sandy. Fluxes at high light conditions were either in the reverse direction of those in the dark, or reduced relative to dark, fluxes, reflecting photoautotrophy. Sediments with smaller grain sizes showed less consistent short-term light responses. In contrast, significant differences in fluxes associated with original depth of sediments (long-term responses) were more common with smaller grain sized sediments. Direction of response was not consistent, however. Overall, we found that the potential impacts of shallow sediments on water quality is very much light dependent.

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ROLE OF SAV BEDS IN ATTENUATING NUTRIENTS, SUSPENDED SEDIMENTS, CHLOROPHYLL, AND LIGHT AT THE HEAD OF THE CHESAPEAKE BAY

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Abstract: Submerged aquatic vegetation (SAV) supposedly increases the sedimentation rates of suspended particulate materials and acts to modulate nutrient inputs. To investigate these processes and additionally for insight into the temporal scaling of inputs to multicosms, intensive monitoring within a submerged vegetated bed and an adjacent unvegetated area was undertaken at the head of Chesapeake Bay. Automated water samplers (ISCO), PAR sensors, and data loggers, as well as Hydrolabs, were employed to obtain fine-scale records of nutrient inputs and physical forcing over three 10-day periods. The largest amount of water ever recorded flowed down the Susquehanna River in April 1993, bringing with it twice the yearly average of sediment, nitrogen, and phosphorus. This region of the Bay has very high temporal variability, with nitrate levels varying as much as 10-190 µM on a time scale of hours, whereas ammonium and nitrite were more stable. Phosphate was usually less than 0.1 µM and appeared to be limiting in the water column, with mean concentrations in the SAV bed reduced to half the outside. Counter to original expectations, we found higher PAR attenuation, suspended particulate concentrations, and chlorophyll levels inside compared to outside the bed. In contrast to the water column, pore-water PO_4 was less variable, but was much higher than previous years. Although solid phase PO_4 was lower than in 1991, we hypothesize that the sediments had reduced oxygenation because *Vallisneria americana* declined in 1993, which lowered eh in the root zone.

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Effects of a Polyhaline SAV Bed on Spatial and Temporal Variability in Water Quality

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Abstract: Beds of submersed aquatic vegetation (SAV) may moderate or enhance the standing stocks of dissolved oxygen, nutrients, suspended particulates, and chlorophyll in water masses that are exchanged with adjacent channel areas of the Bay or its tributaries. This study investigated the short-term variability in commonly measured water column parameters at four stations located along a 1 km transect across a polyhaline SAV bed in the lower Bay. Data were collected for 10-day periods during June, August, and October 1993 at 15 min to 3 hr intervals using automated water samplers, arrays of spherical PAR quantum sensors, and Hydrolab datasondes. A similar companion study was conducted at the head of the Bay during these same periods.

Dissolved inorganic oxygen (DIN) and Dissolved inorganic phosphorus (DIP) levels were generally quite low in this polyhaline region of the Bay during most periods (< 10µM and <1 µM, respectively), however concentrations varied from 1-fold to 10-fold for DIN and 1-fold to 2-fold for DIP at intervals of hours to days. Similar short-term pulses of suspended particles and chlorophyll were also observed. Effects of the SAV meadow on the water column varied with season and the associated meadow development. During June, at maximum SAV biomass, the bed acted to moderate pulses of suspended particles and nutrients, although dissolved oxygen levels varied considerably on a diel basis as a result of the high macrophyte productivity. During August, when bed development was reduced and large amounts of detrital macrophyte production were present, the vegetated shoal appeared to be a source of DIN (especially NH_4), and elevated levels of total suspended solids and Chlorophyll and community respiration were evident compared to channelward stations. During October, when secondary regrowth of SAV was observed and detritus was largely gone, SAV and channel areas were most similar.

INTRODUCTION

The decline of submersed aquatic vegetation (SAV) in tributaries of the Chesapeake Bay has been associated with light limitation resulting from changes in water quality and suspended sediment concentrations (Kemp et al. 1983, Orth and Moore 1983). Eutrophication severely limits the potential for the growth of submersed aquatic macrophytes, not only by promoting planktonic algal blooms, but also by promoting excessive epiphytic algal overgrowth. Evidence for the negative impacts of eutrophication on submersed macrophytes spans northern and southern hemispheres in marine as well as freshwater environments (Stevenson 1988). For example, nutrient loading of coastal salt ponds in New England has been shown to enhance marine macroalgae at the expense of seagrass species (Lee and Olsen 1985, Valiela and Costa 1988), and appears to be associated with a significant decline of seagrasses in Cockburn Sound, Australia (Shepherd et al. 1989).

Because of these and other relationships observed between water quality and declines in living resources in the Bay, the 1987 Chesapeake Bay Agreement called for the development and adoption of guidelines for the protection of habitat conditions necessary to support Bay living resources. In response to this request, habitat requirements for Chesapeake Bay SAV were developed using empirical models of seasonal medians in water quality, and corresponding growth and survival of natural and transplanted SAV at various regions throughout the Bay (Orth and Moore 1988, Batuik et al. 1992, Dennison et al. 1993, Stevenson et al. 1993).

Although general relationships between water quality and SAV response have been defined, a number of questions still remain. Of particular importance in Bay management is the need for a better understanding of the temporal variability of water quality relative to SAV habitat criteria. SAV habitat requirements have been defined based upon seasonal medians using biweekly or monthly sampling of the water column. Only a few studies have investigated short-term variability of certain water quality parameters in shallow SAV sites (Ward et al. 1984). Is there short-term variability in measured parameters at shallow water vegetated, or potentially vegetated, sites that are important considerations for both monitoring programs or ecosystem model simulations? Currently, the sites that are monitored are visited at biweekly to monthly intervals, and most sampling is conducted in mid-channel areas. Although this may provide a relative measure of comparison among areas sampled at similar time scales, the variable exposure levels that are likely influencing plant response in the littoral zone may not be adequately measured. Episodic events such as storms of moderate, regular nature are important forcing functions of the system, but their influence on shallow water conditions has not been well documented. Effects of other regular, physical forcing factors such as tidal influences are not easily interpreted by such data (Hutchinson and Sklar 1993). High-frequency field sampling is necessary not only to define these conditions, but also to validate current ecosystem models that simulate certain parameters using stochastic or other functions.

Spatial variability in water quality relative to SAV habitats is another factor that is an important consideration in the continued development of SAV habitat requirements and restoration targets. Small-scale differences in certain parameters have been documented, such as decreases in the concentration of suspended solids (Ward et al. 1984), that are associated with the baffling effect of the SAV community (Kemp et al. 1984). However, variability of many other factors such as nutrients, or light availability, are not as well-known. SAV beds have the ability to modify their environment, and this may provide one key to their survival. Because of this capacity, it is possible that conditions that permit the continued existence of SAV beds may not be suitable for recovery of denuded sites; or, that conditions that originally caused the declines of SAV beds in the Bay are not the same as those inhibiting recovery.

In this project, we investigated the patterns of variability in water quality, and the resultant effects of SAV, over short spatial and temporal scales. The study site, Goodwin Island, is located near the mouth of the York River in the high-salinity region of Chesapeake Bay (37°12’ N 76°23’ W). It is vegetated with salt-tolerant SAV species (e.g., *Zostera marina* and *Ruppia maritima)*, which declined to low levels in the 1970’s (Orth and Moore 1983), but have been increasing in abundance in recent years (Orth et al. 1992). It is an National Estuarine Research Reserve System (NERRS) site and the location of other ongoing field studies.

METHODS

At the Goodwin Island site, four stations were established along a transect running approximately NW/SE, beginning in the shallow subtidal flat adjacent to the eastern shoreline of Goodwin Island, and extending approximately 1 km channelward. Stations 1 and 2 were located in the SAV bed; station 3 was located at the outer edge of the bed in an area sparsely vegetated with *Z. marina*; and station 4 was located outside the bed in an area of bare sand bottom. At each station a permanent pole, which supported a box that housed the remote sampling equipment, was placed in the bottom.

Water quality at the site was sampled using both intensive (seasonal) and periodic (biweekly) sampling schedules. Intensive sampling was undertaken during four 10-day periods in June, August, and October of 1993, and April, 1994. During each intensive sampling period, water samples were obtained at 3 hr intervals at each station using automated samplers (ISCO, Inc.) (table 1). Biweekly sampling was conducted as part of the regularly scheduled Virginia Near-shore Submerged Aquatic Vegetation Habitat Monitoring Program.

Water samples from the intensive sampling were obtained at fixed depths of 30 cm above the bottom, stored on ice for no more than 24 hours, filtered through .45 µm filters, and then analyzed in duplicate for dissolved inorganic nutrients and suspended particles. Ammonium was determined spectrophotometrically after Parsons et al. (1984). Nitrite, nitrate, and orthophosphate were measured using an Alpkem autoanalyzer, equipped

Table 1. Summary of parameters and sampling intervals for SAV and water quality measurements at the Goodwin Island, Virginia study area.

Parameter	Interval
SAV	
Community transect (% cover) (June, August, October, April)	Periodic
Biomass	
Above/below ground, density , canopy height, attached epiphytes	Monthly
Water quality	
Routine sampling (TSS, K_d, Chla, NO_2,NO_3,NH_4, DIN, PO_4, temperature, salinity)	Biweekly
Intensive sampling	Periodic
TSS (FIM, FOM)	Every 3 hours for 10 days
Chla	"
NO_2	"
NO_3	"
NH_4	"
DIN	"
PO_4	"
K_d	Every 15 min for 10 days
Temperture	"
Salinity	"
DO	"
pH	"
Tidal depth	"
Wind direction/speed	"

with a model 510 spectrophotometer. Total suspended solids (TSS) were determined by filtration, rinsed with fresh water, and dried at 60°C. Filterable inorganic matter (FIM) and filterable organic matter (FOM) were obtained by ashing the material at 550°C. *Chlorophyll a* was extracted using DMSO/acetone (after Shoaf and Lium 1976) and analyzed by fluorometry.

Dissolved oxygen, pH, salinity, temperature and water depth were measured at 15 min intervals using Hydrolab Datasonde instrument systems placed adjacent to the ISCO sampler intakes, and individually calibrated before each field deployment. In situ PAR light attenuation was measured continuously and integrated over 15 min periods using fixed arrays of underwater, scalar, 4 quantum sensors (LI-193SA, [LI-COR, Inc.]). The sensors were calibrated by the manufacturer prior to use, and when deployed in the field were cleaned daily to remove any accumulated epiphytes. Atmospheric, downwelling irradiance (2 quantum, LI-190SA, [LI-COR, Inc)], and 6 min, vector-averaged wind speed and direction were recorded continuously at the Gloucester Point, Virginia, meteorological station (height +45 m mean sea level).

Biweekly water samples were obtained in triplicate, at a depth of 0.25 m at station 2, and placed on ice until returned to the laboratory for analysis of dissolved nitrite, nitrate, ammonium, orthophosphate, Chla, TSS, FIM, and FOM. Triplicate analyses were made in situ for DO, pH, water temperature, salinity, and integrated water column Kd (2 quantum, LI- 92SA, [LI-COR, Inc.]).

Monthly, from May, 1993, through April, 1994, measurements of macrophyte biomass were determined at each of the vegetated stations.

Friedman's ANOVA (Zar 1984), a nonparametric procedure for testing repeated measures, was used to compare evaluate dissolved nutrients, total suspended solids (TSS), Chl*a*, and physical parameters for significance differences among stations within each sampling period. Analyses were accomplished using Statistica /Mac(StatSoft Inc., Tulsa, Oklahoma). If differences among stations were determined significant ($P \leq .01$), multiple, pairwise comparison analysis (Zar 1984) was used to test individual means.

RESULTS AND DISCUSSION

The macrophyte community structure in the SAV bed was characterized by increasing biomass April dominated by *Z. marina*, highest biomass of *Z. marina* in June (³250 gdm m^{-2}), a dieback in *Z. marina* and increased biomass of *R. maritima* in August, and a dieback of *R. maritima* and a slight regrowth of *Z. marina* in October. Epiphyte abundance were consistently greater on *R. maritima* than *Z. marina* throughout the year. Epiphyte loads were lowest in April and June, and greatest in August and November.

Diurnal patterns of dissolved oxygen demonstrated greater range within the beds compared to outside, illustrating higher metabolic activity per volume of water in the shallows. Daily mean and maximum DO levels were higher in the beds than in adjacent channel areas during periods of maximum SAV growth and biomass. In August, DO minimums each night were accompanied by increased water column levels of PO_4, presumably due to release of PO_4 from the sediment. These increases were reduced to background levels during the day.

Table 2a. Means of inorganic nutrients and suspended particles by station for June 1993 and August 1993 study periods at Goodwin Island. Units of measure: mg l-1, for basic parameters; µM for parameters in parentheses; I.µg11 for *chla*. Identical superscript letters denote no significant differences ($P > 0.05$) among stations within each study period.

		June 1993 Station 2	Station 3	Station 4
NO_2	0.0008 ^{a}	0.0008 ^{a}	0.0002 ^{a}	0.0009 ^{a}
	(0.059)	(0.058)	(0.084)	(0.063)
NO_3	0.0042 ^{a}	0.0033 ^{a}	0.0054 ^{a}	0.0066 ^{a}
	(0.298)	(0.235)	(0.383)	(0.473)
NH_4	0.0186 ^{a}	0.0202 ^{a}	0.0196 ^{a}	0.0335 ^{a}
	(1.33)	(1.45)	(1.40)	(2.39)
DIN	0.0239 ^{a}	0.0247 ^{a}	0.0263 ^{a,b}	0.0414 ^{b}
	(1.71)	(1.76)	(1.88)	(2.96)
PO_4	0.015 ^{a}	0.015 ^{a}	0.015 ^{a}	0.015 ^{a}
	(0.46)	(0.48)	(0.48)	(0.47)
TSS	4.21 ^{a}	4.64 ^{a}	8.48 ^{b}	7.67 ^{b}
Chla	8.67 ^{a}	14.90 ^{b}	23.78 ^{c}	24.49 ^{c}
		August 1993		
NO_2	0.0019 ^{a}	0.0010 ^{b}	0.0007 ^{b}	0.0006 ^{b}
	(0.137)	(0.071)	(0.047)	(0.044)
NO_3	0.0044 ^{a}	0.0036 ^{a}	0.0042 ^{a}	0.0042 ^{a}
	(0.316)	(0.259)	(0.301)	(0.303)
NH_4	0.028 ^{a}	0.022 ^{b}	0.015 ^{b}	0.017 ^{b}
	(2.03)	(1.60)	(1.09)	(1.18)
DIN	0.035 ^{a}	0.026 ^{b}	0.020 ^{b}	0.022 ^{b}
	(2.47)	(1.89)	(1.43)	(1.54)
PO_4	0.011 ^{a}	0.0096 ^{a}	0.014 ^{a}	0.010 ^{a}
	(0.368)	(0.310)	(0.453)	(0.319)
TSS	4.91 ^{a}	7.79 ^{b}	4.42 ^{a}	4.71 ^{a}
Chla	10.82 ^{a}	12.64 ^{b}	9.77 ^{a}	10.94 ^{b}

Table 2b. Means of inorganic nutrients and suspended particles by station for October 1993 and April 1994 study periods at Goodwin Island. Units of measure: mg l-1, for basic parameters; µM for parameters in parentheses; .µg11 for *chla*. Identical superscripts denote no significant differences (P>0.05) among stations within each study period.

		October 1993 Station 2	Station 3	Station 4
NO_2	0.0015 ^{a}	0.0024 ^{a}	0.0010 ^{b}	0.0007 ^{b}
	(0.105)	(0.174)	(0.073)	(0.043)
NO_3	0.0072 ^{a}	0.0085 ^{a}	0.0121 ^{b}	0.0114 ^{b}
	(0.518)	(0.610)	(0.864)	(0.815)
NH_4	0.033 ^{a}	0.028 ^{a}	0.026 ^{a}	0.038 ^{a}
	(2.35)	(1.99)	(1.88)	(2.70)
DIN	0.042 ^{a}	0.039 ^{a}	0.039 ^{a}	0.050 ^{a}
	(2.96)	(2.77)	(2.82)	(3.56)
PO_4	0.0087 ^{a}	0.010 ^{a}	0.0194 ^{a}	0.0090 ^{a}
	(0.280)	(0.325)	(0.627)	(0.290)
TSS	5.65 ^{a}	6.06 ^{a,b}	5.82 ^{a,b}	6.72 ^{b}
Chla	6.34 ^{a}	10.11 ^{b}	15.96 ^{c}	15.04 ^{c}
		April 1994		
NO_2	0.003 ^{a}	0.006 ^{b}	0.007 ^{c}	0.006 ^{b}
	(0.224)	(0.417)	(0.500)	(0.453)
NO_3	0.020 ^{a}	0.084 ^{b}	0.125 ^{b}	0.127 ^{b}
	(1.45)	(6.03)	(8.90)	(9.08)
NH_4	0.019 ^{a}	0.017 ^{a}	0.018 ^{a}	0.015 ^{a}
	(1.37)	(1.22)	(1.31)	(1.09)
DIN	0.047 ^{a}	0.108 ^{b}	0.153 ^{c}	0.152 ^{c}
	(3.33)	(7.70)	(10.91)	(10.84)
PO_4	0.0095 ^{a}	0.0089 ^{a}	0.0101 ^{a}	0.0074 ^{a}
	(0.297)	(0.278)	(0.315)	(0.230)
TSS	2.85 ^{a}	2.64 ^{a}	3.12 ^{a}	4.68 ^{b}
Chl*a*	19.12 ^{a}	25.50 ^{b}	28.35 ^{b}	27.72 ^{b}

Table 2a and 2b present the means of inorganic nutrients and suspended particles by station for the June, August, October, and April study periods.

The principal nitrogen species during all study periods, except for April, was NH_4. This is sometimes referred to as “old”, or regenerated, nitrogen as compared to NO_3 or “new”, nitrogen whose primary source is the watershed. Considering that this site is near the mouth of the Bay, and farthest removed from river inputs, the dominance of NH_4 observed is not surprising and has been well documented. Only during April, when riverine inputs were the highest of all the study periods was NO_3 the dominant species.

Uptake of dissolved inorganic nitrogen (DIN) was observed during periods when macrophyte abundance was high in April and June. During periods of highest water temperatures and therefore increased microbial activity, regeneration of NH_4 was observed inside the SAV bed. Net uptake of NO_3 in the spring was replaced by net regeneration of NH_4 in the summer. Rapid uptake of DIN by the macrophyte community reduces the pool of nutrients available for phytoplankton growth. This may be especially important in the lower Bay, where nitrogen levels are lower. In areas of transitional water quality, the existence of large established beds of SAV may improve local conditions for their continued survival during years of high runoff. Small isolated patches may be overwhelmed. In the upper Bay site, DIN is in excess abundance and is apparently not limiting to epiphyte or phytoplankton growth.

Table 3 presents a summary comparison of median levels of five key water quality parameters that have been used to define habitat requirements for SAV growing in polyhaline regions of Chesapeake Bay (Batiuk et al. 1992). Polyhaline SAV habitat requirements have been defined as median levels of these particular water quality constituents measured at regular intervals during the growing season, which correspond to areas where SAV beds have remained persistent in the highest salinity regions of the bay (Moore 1992). Results of biweekly monitoring of water quality at station 2 on Goodwin Island in 1993 demonstrate that this SAV bed would have met all criteria except that for Chl *a* during this year. These results support the habitat criteria concept, where similar comparisons have demonstrated that all or all but one of the habitat requirements will be met in areas where SAV are persistent.

Medians of each intensive monitoring study at station 2 are presented for comparative purposes. For the five parameters, the habitat requirement criteria were exceeded only twice: during October, 1993 for K_d, and during April 1994 for Chl*a*. K_d medians in October are influenced by high K_d values during the morning and afternoon. During the April study period, high levels of dissolved inorganic nitrogen (DIN) (mostly NO_3) are supportive of the highest levels of phytoplankton observed. Quantitative comparison with the biweekly sampling results is difficult, because both sets of medians reflect different intensities and duration of sampling. Obviously, the biweekly sampled growing season medians do not reflect the short term or seasonal variability associated with this site. In areas of marginal water quality this variability could be important in determining long-term success of the SAV. The biweekly growing season medians however, do, appear to accurately characterize the water quality classification of this area in regard to SAV requirements. They provide an overall measure of water quality that is similar to that presented by the short-term, hourly sampling.

Growing season medians were also determined using surface data from adjacent, mainstem monitoring stations. These medians when compared to similar, biweekly data for station 2, inside the bed, are identical for K_d, higher for TSS and DIN, and lower for Chl*a* and DIP (table 3). Habitat requirement levels were not exceeded for any of the parameters. Of the five parameters investigated, only TSS and DIP seem to be somewhat out of line with values from the shallow water site. These differences may also reflect differences in methodologies. At a deeper water, mainstem station, TSS might be expected to consist in large part of Chl*a*. However, Chl*a* levels are lower here than at station 2. DIP, which were generally consistent at the Goodwin Island stations, were much lower at the mainstem monitoring station. When the mainstem data are compared to seasonal medians from the channelmost, intensive monitoring station 4, similar results are obtained. Both TSS are higher and DIP are lower at the mainstem station than any of the seasonal medians at station 4. Although there are some differences with data from the intensive studies, overall, the mainstem monitoring data do support the conclusion that water quality in this area meets the SAV habitat criteria, and therefore SAV should be successful in this region.

Seasonal, study period medians from both inside the SAV bed, at station 2 and outside SAV bed at station 4 are very similar (table 3). During June 1993, median levels of Chl*a* exceeded the habitat limits at station 4 and not at station 2, while during April 1994, DIN was also exceeded at station 4 and not at station 2. These differences, potentially, reflect the ability of SAV beds to baffle suspended particles and take up nutrients, especially during periods when SAV growth and bed development is high. These results suggest that during certain seasonal periods, established SAV can improve water quality sufficiently within the bed to achieve the habitat criteria limits when the adjacent water mass is above the criteria. Obviously, these habitat criteria are only yardsticks that provide a general measure of SAV/water quality relationships, however, these results suggest that during seasonal pulses in reduced water quality, the existence of beds provides a positive feedback that may enhance their continued growth and survival.

Although biweekly sampling does not capture the diel, tidal, and other pulses or variability in water column constituents that we observed in these studies, they do provide a reasonable characterization of water quality levels in these areas. Daily variability may exceed seasonal variability for most parameters measured, but the median levels of these constituents are near the lower levels observed, and the high pulses are short lived. Thus only infrequently will the pulses be measured in the biweekly sampling. Many times these pulses will occur at

Table 3. Summary comparison of polyhaline SAV habitat requirements for five key water quality parameters. Median levels are calculated using (1) 1993 growing season biweekly monitoring at station 2; (2) station 2 seasonal, intensive study data; (3) 1993 growing season, biweekly monitoring data at two nearest Bay mainstem monitoring stations (WE4.2/4.3); and (4) station 4 seasonal, intensive study data.

Key Water Quality Parameters	Polyhaline SAV *Habitat Requirements	1) Goodwin Station 2 Biweekly Monitoring	2) Goodwin Intensive Monitoring Station 2 (inside SAV)				3) Mainstem WE4.2/4.3 Biweekly Monitoring	4) Goodwin Intensive Monitoring Station 4 (outside SAV)			
			June	Aug	Oct	Apr		June	Aug	Oct	Apr
K_d (m^{-1})	1.5	**1.3**	1.2	1.0	1.7	1.1	**1.3**	1.7	0.9	1.2	0.88
TSS ($mg\ l^{-1}$)	15	**7.8**	3.7	6.0	4.9	2.5	**13.0**	6.9	4.6	6.5	4.9
Chl*a* ($\mu g\ l^{-1}$)	15	**16.8**	13.6	10.8	8.8	23.2	**9.7**	23.8	10.4	13.9	24.2
DIN (μM)	10	**1.5**	1.3	1.5	2.4	6.84	**2.8**	1.5	1.3	3.3	11.3
($mg\ l^{-1}$)	(0.14)	**(0.02)**	(0.02)	(0.02)	(0.03)	(0.10)	**(0.04)**	(0.02)	(0.02)	(0.05)	(0.16)
DIP (μM)	0.67	**0.50**	0.44	0.30	0.40	0.33	**0.10**	0.47	0.60	0.30	0.29
($mg\ l^{-1}$)	(0.02)	**(0.02)**	(0.02)	(0.01)	(0.01)	(0.01)	**(0.004)**	(0.02)	(0.02)	(0.01)	(0.01)

*From Batiuk et al. 1992

night or during storm events and they will not be sampled with infrequent, point sampling. However, the monitoring will likely capture the median conditions, which in turn are most important for SAV response. In both areas studied here growing season medians were below the habitat requirements thresholds set for each area. Thus, they correctly predicted that these areas should be suitable for SAV growth.

In areas of limiting or transitional water quality however, these infrequent pulses may be limiting SAV survival. Thus, certain areas that meet median water quality levels but have no SAV may be limited by irregular high levels of TSS or nutrients that are not effectively measured by biweekly sampling. In addition, slight year-to-year variations in water quality conditions during the growing season are unlikely to be effectively measured by biweekly or less-frequent sampling. Therefore establishing why SAV expanded in distribution one particular year compared to another, especially in areas of transitional water quality, may not be possible. Trends may be identified using 3 or 4 years of data records. For example, water quality in one particular region during the late 1980s may be compared effectively to that of the late 1990s. This can only be obtained by maintaining long term monitoring programs of this type.

Records of seasonal, short-term, site-specific variability such as investigated here are also highlighted. Not only do they provide a more integrative view relationships between SAV and water quality, and processes relating the two, but they provide a test of the effectiveness of the more spatially distributed, infrequent data.

Except in areas where groundwater or local upland runoff is high, mid-channel nutrient concentrations are useful to characterize the long-term inputs or stresses to the macrophyte, or potential macrophyte, areas. Where SAV occurs, concentrations inside the beds can be quite different than outside. These differences reflect the net effect of the SAV bed community on the particular water quality constituent. As the field studies demonstrate, rapid uptake and release of inorganic nutrients can occur by the SAV, algal, heterotrophic, and microbial components of the system. Therefore, nutrient concentrations outside the bed better reflect long-term system impacts on SAV areas than concentrations measured within large SAV meadows, especially where water residence time is high. In areas where SAV beds are small and scattered, or where water velocities are high and residence time is short, concentrations of nutrients within the beds better reflect channel concentrations.

Other important variables, including suspended particle load and light attenuation, can also be quite different in and out of existing beds. However, because the macrophyte communities are integrating the light available to them, not the light available outside of the bed, measurements should be made over the vegetated areas. In shallow water areas this water column attenuation may be more or less than in the channel. In sparsely vegetated areas, these differences may be more similar than in areas with extensive vegetation. Estimates of these differences are needed if models relating water quality to SAV are to be accurate. In certain areas, such as regions of marginal water quality in the lower Bay, persistence of vegetation is likely related to the capacity of the vegetation to improve water clarity. In the lower Bay, limiting conditions earlier in the year may be reducing survival during the summer. Natural year-to-year variability in SAV may also may be related not only to annual differences in water quality, but also to the normal interrelationships between SAV and bay waters. In one possible scenario, optimum growing conditions and extensive growth of an eelgrass bed during the spring lead to the effective trapping of suspended particles and algae. The decomposition of this biomass along with the large SAV biomass within the bed causes an increase in sediment oxygen demand, which reduces SAV growth during the summer, resulting in a unusually large late-summer decline.

ACKNOWLEDGEMENTS

Funds for this research were provided by the Chesapeake Bay Program, Cooperative Agreement CB003909.

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Toward a Sustainable Coastal Watershed:
The Chesapeake Experiment. Proceedings of a Conference
1-3 June 1994. Norfolk, VA
Chesapeake Research Consortium Publication No. 149

Sediment Characteristics and Inorganic Fluxes Associated with Vegetated and Nonvegetated Subtidal Habitats of the Goodwin Islands, Virginia

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Abstract: The Goodwin Islands Ecosystem is a National Estuarine Research Reserve location and consisting of about 200 ha of intertidal mudflat and marshes surrounded by about 600 ha of vegetated and nonvegetated subtidal habitats extending to the -2.0 m depth contour. It is hypothesized that vegetated subtidal and intertidal habitats are seasonal sources of oxygen and fixed carbon and sinks for inorganic nutrients while sediments represent longer- term carbon storage for the ecosystem as a whole. This study focuses upon subtidal sediment microalgal distribution and biomass, sediment organic and inorganic content, and sediment/water oxygen and nutrient exchange processes in vegetated and nonvegetated habitats. Sediments and microalgae are sampled according to a stratified randomized design and flux measurements are performed on large, intact sediment/water cores. Preliminary analysis of sediment characteristics and microalgal biomass shows great spatial variability over the subtidal environment and seasonal flux studies have supported the source/sink hypothesis. Nonvegetated subtidal habitats appear to contain sufficient sediment microalgal biomass to maintain autotrophic status throughout much of the year. Sampling of subtidal and intertidal sediment characteristics and microalgal biomass will continue during 1994. The results of this study will be compared to simulated sediment stocks and processes derived from a dynamic spatial model of ecosystem primary production being developed for the Goodwin Islands ecosystem.

INTRODUCTION

The Goodwin Islands National Estuarine Research Reserve is a pristine, polyhaline littoral ecosystem in lower Chesapeake Bay that includes intertidal marshes and mudflats surrounded by a wide, partially vegetated subtidal shoal that extends to the -2.0 m depth contour (MLW). The subtidal shoal constitutes almost 70% of the entire ecosystem area (810 ha) and supports eelgrass (*Zostera marina L.*), widgeongrass (*Ruppia maritima*), macroalgae, and sediment microalgal communities with variable distribution and production. Tidal advection, sediment organic decomposition, and water column heterotrophic regeneration provide inorganic nutrients for the primary productivity of the macrophytes, sediment algae, and phytoplankton (Fisher et al. 1982, Rizzo 1990). Sediment/water inorganic exchanges are a primary mechanism of linking sediment and water column processes in estuaries and can be more seasonally variable than either primary or secondary production (Asmus 1986). Physical factors such as insolation, wind, and tidal currents and biological processes such as autotrophic uptake and nitrification/denitrification influence the sediment and water concentrations of inorganic nutrients (Asmus 1986, Rizzo 1990). Sediments with sufficient insolation to support rooted macrophytes and microalgal communities are often net autotrophic (Asmus 1986, Rizzo 1990). Approximately 38% of the subtidal York River estuary is less than the historical -2.0 m depth maximum for eelgrass survival and maintains a photic sediment environment (Rizzo 1990).

OBJECTIVE

The primary objective of this study was to investigate seasonal and spatial variability in sediment characteristics and sediment/water inorganic exchanges for the subtidal environments of the Goodwin Islands Ecosystem. This study is part of two larger studies on spatial and temporal processes over the various habitats of the Goodwin Islands ecosystem. One study utilized continuous, platform sampling of water column variables such as temperature, light, and nutrients to analyze seagrass habitat criteria (Moore and Goodman, 1995). The other study employs a hypsometric approach to integrate modelling, geographic, and field data in the analysis of intertidal and subtidal pattems and productivity. The data presented in this paper were collected during spring and summer 1993.

METHODS

An area approximately 200 m x 1000 m from nearshore to farshore was divided into 260 numbered grids. This area encompassed the monitoring platforms of the Moore and Goodman intensive study (figure 1). Three primary habitats (farshore nonvegetated, eelgrass meadow, nearshore partially vegetated) were delineated within the grids and used as individual strata for a stratified random sampling design in order to determine overall sedi-

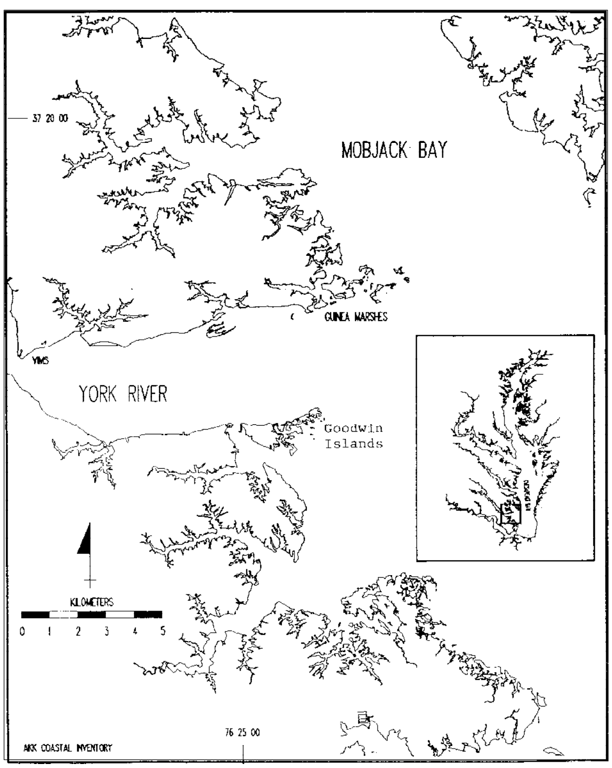

Figure 1. Location map of the Goodwin Islands in the lower York River.

ment characteristics and *chlorophyil a* (Chla) (concentrations. Four replicate cores (5.6 cm ID x 10.0 cm) for sediment characteristics and 5-7 replicate cores (2.4 cm ID x 1.0 cm) for sediment chl a (were randomly selected from each of the three strata during May/June and August 1993. The large sediment cores were extruded and sectioned into 0-2, 2-5, and 5-10 cm increments. Increment fractions were then either weighed wet, dried at 60° C, and combusted and weighed again to determine water and organic contents or were extracted in 2 N KCI for 10 minutes for nutrient analysis. The centrifuged and filtered extracts were analyzed for total extractable $NH4^+$ in nmol gdw^{-2} I using the phenolhypochlorite technique. Total extractable NO_{x-} (NO_{3-} + NO_{2-}) was determined using a Alpkem AutoAnalyzer (APHA 1992). The small cores were extruded and sectioned into 0-2, 2-5, and 5-10 mm sections using a microsectioning device. The sections were placed into scintillation vials, frozen overnight, and then extracted with 10 ml of a 4.5:4.5:1 solution of methanol: acetone: water (Pinkney et al. in press). The sections were kept in a dark freezer and shaken daily until the third day. The concentration of chl*a* (and total phaeopigments were determined in filtered extracts by measuring the absorbances at 750 and 665 nm before and after acidification with 10% HCI (Lorenzen 1967).

Seasonal subtidal sediment/water inorganic exchange studies (SONE) were also conducted to quantify vertical fluxes and identify community trophic status. Within the seagrass habitat, 3-5 large cores (I 1.6 cm ID x 15 cm) were selected from each of vegetated and nonvegetated patches. The water overlying the sediment within a core was replaced with filtered, partially degassed water from the field site. These cores were placed in a flowing seawater bath of the outdoor mesocosms at the Virginia Institute of Marine Science (VIMS) at Gloucester Point, Virginia. The cores were stirred using battery-powered submersible motors and were incubated for 4-6 daylight hours. Dissolved oxygen and inorganic nutrients in the overlying water were sampled hourly. Oxygen was measured using an Orbisphere Oxygen probe while aqueous nutrients were analyzed using the colorimetric methods previously described. Concentrations in gmoles L^{-1} were multiplied by overlying water volume to derive mass (limoles) and then divided by core surface area (0.0105) to derive units of li moles m^2. The concentrations were then plotted over time using linear regression to determine the slope (or rate of change) in gmoles m^2 hr^{-1}.

RESULTS

Table 1 provides an overview of the subtidal sediment characteristics during spring and summer 1993. In both May/June and August 1993, sediment/ water and organic content decreased with distance from the shoreline. Sediment organic content was highest in nearshore areas (1.86% and 1.48 % during May/June and August, respectively). Within each season, total extractable NH^{4+} was greatest in the eelgrass meadow (table 1). The spring sampling occured at the time of greatest eelgrass biomass in Chesapeake Bay and NH_{4+} concentrations were higher than during the summer (86.17 versus 34.06 nmol gdw-I). During May/June 1993, total extractable NO^{x-} was greatest in the eelgrass meadow (1.22 nmol gdw-1) although the nonvegetated sediment concentration was similar (1.06 nmol gdw^{-1}). The nonvegetated sediment concentration was highest in August 1993 (0.93 nmol gdw^{-1}) and the concentration for each sediment type was less than measured in May/June 1993. Sediment chl*a* (concentrations were similar among nonvegetated, eelgrass, and nearshore partially vegetated sediments in both May/June (41.06, 36.49, 30.96 Mg m^{-2}) and August 1993 (23.85,29.81,30.11 Mg m^{-2}).

The net exchanges of NH_{4+}, NO_{x-}, and $P0_{-3}$ for the vegetated and nonvegetated subtidal sediments for May/June and August 1993 are shown in figures 2 and 3. Vegetated sediments in May/June experienced a net production of NH4+ while NO_{x-} and $P0_{-3}$ were removed from the water column (figure 2). The NH_{4+} efflux was perhaps a function of the high NH_{4+} concentrations measured in the eelgrass sediments during this time (table 1) and was significantly different than the NH^{4+} uptake experienced by the non- vegetated sediments (figure 2). $P0_{-3}$ immobilization was greater in the vegetated sediments than the nonvegetated sediments during the incubation period (figure 2). During the August 1993 experiment both the vegetated and non-vegetated sediments removed NH_{4+}, NO_{x-}, and $P04_{-3}$ from the overlying water.

DISCUSSION

The Goodwin Islands ecosystem includes a wide subtidal shoal that is sandy offshore and progressively more organic over a gradient that leads inevitably to a peaty intertidal marsh (table 1). Sediment microalgal chl*a* (concentrations are consistent over the spring, summer, and fall (table 1 and Buzzelli unpublished data) while eelgrass is abundant primarily in the late spring. Eelgrass communities have the capacity to trap organic matter, which leads to enhanced sediment

Table 1. Subtidal sediment charateristics for the Goodwin Islands ecosystem nonvegetated farshore, eelgrass meadow, and partially vegetated nearshore habitats during spring and summer 1993. Values are 0-10 cm means ± SE. Concentrations of total extractable NH_{4+} and NO_{x-} (nitrate + nitrite) are reported in nmol gdw^{-1}. Values for Chl*a* are 0-1.0 cm ± SE and are reported in mg m^{-2}.

	%H_2O	%Organic Matter	NH_4^+ nmol gdw^{-1}	NO_x^- nmol gdw^{-1}	Chla mg m^{-2}
MAY/JUNE 1993					
NonVeg Farshore	21.65±0.20	0.83±0.13	43.45±6.98	1.06±0.30	41.06±4.86
Eelgrass Meadow	26.52±1.39	1.14±0.15	86.17±10.92	1.22±0.20	36.49±5.70
PartVeg Nearshore	29.65±1.76	1.86±0.14	34.03±3.85	0.59±0.21	30.96±1.83
AUGUST 1993					
NonVeg Farshore	18.80±0.48	0.35±0.02	19.86±3.29	0.93±0.13	23.85±2.04
Eelgrass Meadow	21.45±0.63	0.78±0.10	34.06±3.37	0.76±0.08	29.81±2.80
PartVeg Nearshore	24.03±0.52	1.48±0.09	24.27±4.38	0.13±0.03	30.11±6.94

nitrogen concentrations. The eelgrass meadow sediments in 1993 contained higher concentrations of NH_{4+} than either farshore or nearshore nonvegetated habitats (table 1). The increased concentration may be responsible for the net NH_{4+} efflux measured from the vegetated sediments during May/June 1993 although NH4+ exchanges vary widely with microbial metabolic processes such as remineralization, nitrification, and denitrification (Asmus 1986). This is the only example provided here of NE_{4+} efflux as all the other cases resulted in sediment uptake of inorganic N and P (figures 2 and 3). Although calculations are often performed to show the potential for sediment nutrient regeneration to support water column primary production (Fisher et al. 1982, Rizzo 1990), studies involving photic sediments often result in net nutrient flux into the sediment (Asmus 1986, Rizzo 1990). The use of microcosms influences the interpretation of the results as ambient physical factors such as wind and tidal mixing were excluded. Physical processes can sometimes mask the predominant biogeochemical exchanges in the environment (Fisher et al. 1982; deJonge and Colijn 1994) and the Goodwin Islands is a relatively open system (figure 1).

Sediment microalgae are significant components of shoal biogeochemical processes owing to their wide distribution, nutrient uptake capacity, productivity, vertical m-igration, and resuspension (Asmus 1986, Rizzo 1990, dejonge and Colijn 1994). Seasonal to annual mean sediment chl*a* is proportional to primary production based upon the C:Chl a (ratio (deJonge and Colijn 1994). The Goodwin Islands ecosystem is approximately 800 ha in size and includes nonvegetated and vegetated subtidal and intertidal habitats, all containing sediment microalgal communities (Buzzelli unpublished data). Microalgae occupy a 1-5 cm surface sediment layer in which to migrate and regulate their physiology, and this surface layer probably plays an important role in the vertical exchanges of inorganic nutrients between deeper sediment layers and the overlying water column. More research is needed on the effects of sediment microalgae upon shoal water column productivity and biogeochemical cycling.

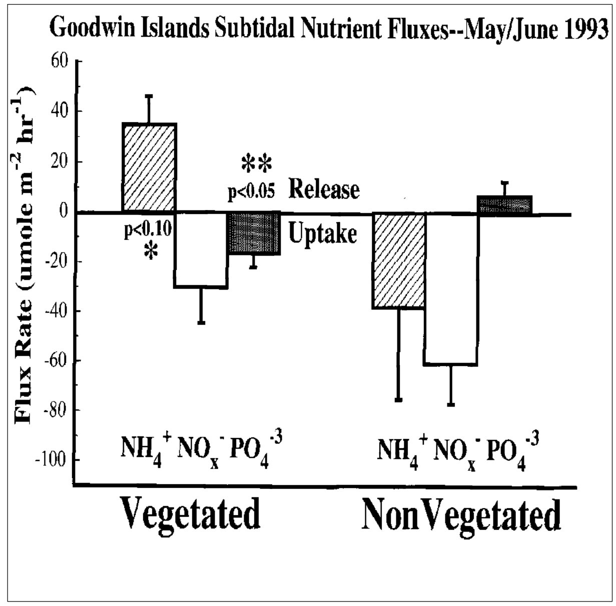

Figure 2. Flux results for May/June 1993. A positive flux value (umoles @ 2 hr^{-1}) indicates a net release of the nutrient from the sediment while a negative flux denotes uptake by the sediment.

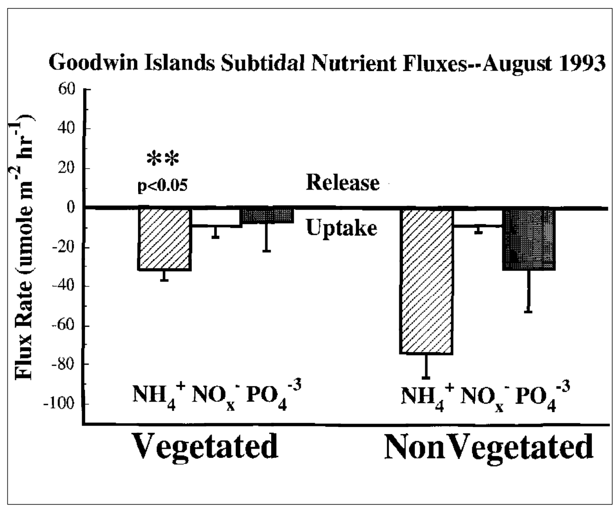

Figure 3. Flux results for August 1993. A positive flux value (umoles m^{2} hr^{-1}) indicates a net release of the nutrient from the sediment while a negative flux denotes uptake by the sediment.

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Toward a Sustainable Coastal Watershed:
The Chesapeake Experiment. Proceedings of a Conference
1-3 June 1994. Norfolk, VA
Chesapeake Research Consortium Publication No. 149

The Importance of Riparian Forests and Nearshore Environments in Reducing Groundwater Nitrogen Loadings to Adjacent Coastal Waters

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Abstract: While significant progress has been made in reducing phosphorus inputs from nonpoint sources to Chesapeake Bay, reduction of nitrogen loadings has yet to be achieved. Groundwater discharge of fresh water to estuarine systems can be substantial and has been implicated in the nitrogen enrichment of coastal systems. The shallow, unconfined aquifers in the mid-Atlantic coastal plain display characteristics that are conducive to groundwater nitrogen contamination and subsequent transport into estuarine environments. Combined with high-risk aquifer characteristics, intensive agriculture practices and urban land uses within the coastal plain increase the potential for aquifer degradation. Because fresh groundwater discharge from unconfined aquifers is generally recognized as a nearshore phenomenon, interception and remediation of nitrate-contaminated groundwater can occur in upland, intertidal, or nearshore regions prior to its discharge into adjacent surface waters. Research efforts have focused on the microbial mediated process of denitrification, which is a primary mechanism for reducing groundwater nitrate levels in mesic forest and nearshore environments. Spatial variations in soil/sediment environments of well-drained upland soils, poorly drained forest soils, and nearshore sediments result in significant vertical difference in denitrification potential rates and limiting substrate factors (carbon and nitrate). Given the nitrogen loading rates and reduced potential for denitrification in well-drained upland regions, riparian forest and nearshore environments provide an environment more conducive to denitrification and subsequent remediation of nitrate-ladened groundwater.

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Deposition of Inorganic and Organic Phosphorus in Maryland in Maryland Tidal Marshes: A Preliminary Analysis

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INTRODUCTION

The environmental degradation of Chesapeake Bay is thought to be the result of excess nutrient inputs, primarily'nitrogen and phosphorus. The major sources of these nutrients include diffuse and point-source inputs from the watershed, atmospheric deposition, and phosphorus inputs from the coastal ocean (Boynton et al. 1994). The long-term burial of phosphorus in subtidal sediments is the ultimate fate of virtually all of the phosphorus inputs, and fluxes to subtidal sediments have received considerable attention. Chesapeake Bay tidal marsh sediments also retain phosphorus, although the form and burial rate of phosphorus have not been examined prior to this study. This study seeks to determine the relative importance of tidal marsh sediments in nutrient retention by examining deposition in three National Estuarine Research Reserve sites included in northern Chesapeake Bay. If tidal marsh sediments are an important sink for nutrients, their proper management in the Chesapeake Bay area is critical to the Bay's ecology.

Our approach to determining the rate of nutrient burial in northern Chesapeake marshes involves the dating of cores using ^{210}Pb techniques to estimate sedimentation rates and the measurement of nutrient concentrations in vertical core profiles. While we have determined the concentrations of phosphorus in numerous cores, the quantification of burial rates awaits completion of ^{210}Pb dating. In this paper, we show the concentrations and forms of phosphorus buried in several different marsh sites, including Patuxent River, Monie Bay, and the Choptank River. The importance of tidal marshes to phosphorus retention examined relative to the total inputs of phosphorus to the system. An earlier study of Choptank River marshes lead to the rough estimate that 5 - 10% of phosphorus loading from atmospheric and watershed inputs was retained in marsh sediments (Stevenson 1991).

This study of phosphorus deposition in Chesapeake Bay marshes includes all three National Estuarine Research Reserve System (NERRS) sites. The Monie Bay site is located on Maryland's Eastern Shore, in Somerset County (figure 1). The marsh system consists of three main tidal creeks draining agricultural and undisturbed watersheds. The salinity ranges from 0-17 ppt (Cornwell et al. 1990, 1994) with vegetation dominated by *Spartina alterniflora*. Much of the nutrient input to this system is the result of drainage from surrounding agricultural fields. Ward et al. (1988) have shown that this marsh system experiences marsh loss from a rise in sea level .

Jug Bay is located on the Patuxent River in Anne Arundel County, Maryland. The research reserve is predominantly freshwater, with maximum salinities reaching only 0.5 ppt in late summer (Swarth and Peters 1993). Vegetation at our sampling sites included *Nuphar* spp. (spatterdock) and *Peltandra Virginica* (arrow arum). As in other tidal fresh marshes, the vegetation at this site is lost from the marsh surface in the winter months, potentially promoting nutrient loss from the system by erosion.

Otter Creek is located just north of Baltimore, Maryland on the Bush River. The watershed surrounding the marsh is heavily developed. Plant

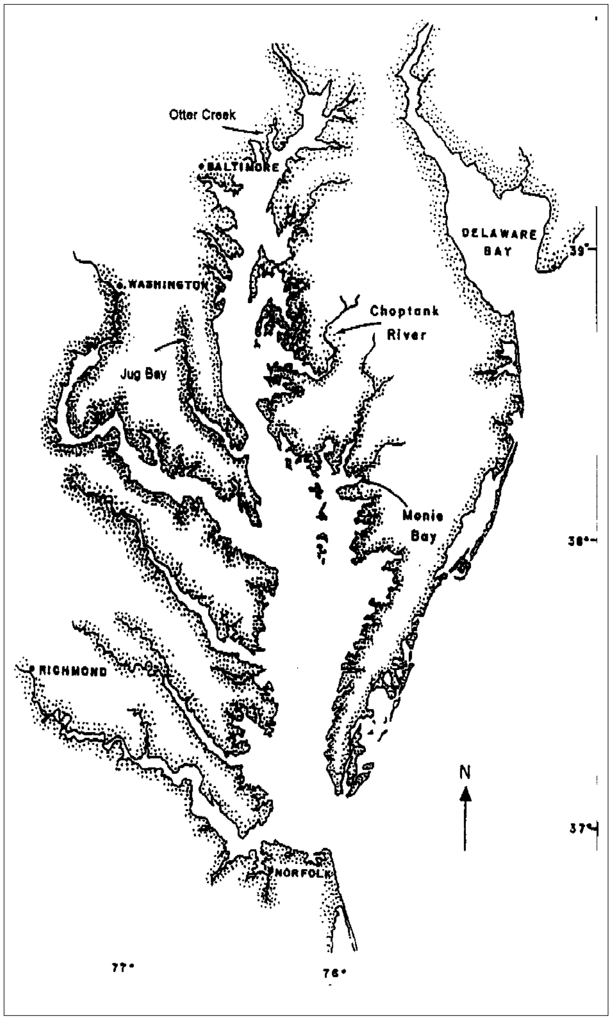

Figure 1. Study site locations on Chesapeake Bay.

communities here show little sign of physical disturbance and include *Typha* spp., P. virginica, *Nuphar* spp. and *Pontederia cordate* (pickerel weed). Salinities at this site range reach a maximum of 3 ppt. Sampling of this site commenced during the summer of 1994.

The Choptank River is the largest tributary on the Eastern Shore and drains mostly agricultural and forested watersheds and was sampled in 1991 for marsh nutrient concentrations. Cores were collected from three sites in the upper Choptank River and three sites in a marsh at the Horn Point Environmental Laboratory. This system has experienced elevated inputs of nitrogen and phosphorus from nonpoint sources, primarily agriculture (Stevenson et al. 1993). Salinities at the sites range from 0 to 15 ppt, depending on location.

METHODS

A McAuley corer was used to sample the sediments (Bricker et al. 1989). Cores were extracted and immediately divided into 3 or 5 cm samples to a depth of 1 meter. Samples were placed on ice and returned to the laboratory where they were dried at 65°C and ground with a ceramic mortar and pestle.

Total phosphorus was determined by ashing the sediments at 550°C and extracting phosphorus with HCI (Aspila et al. 1976). Inorganic phosphorus was measured in the same manner, using an unashed sample. Organic phosphorus was estimated as the difference between these two measurements. Inorganic phosphorus was determined in the extracts by colorimetry. Sediment burial mtes ($g\ m^{-1}\ yr^{-1}$) for six Monie Bay sites were taken from Ward et al. (1988) and P deposition rates were calculated as the product of the burial rate and the phosphorus concentration (mg P g/l) to detemine the overall retention rate of phosphorus on an areal basis. Future calculations will be based on ^{210}Pb.

RESULTS

All phosphorus profiles in this study show surface enrichment of organic and inorganic phosphorus (figure 2). Monie Bay organic phosphorus concentrations remain fairly constant with depth, and inorganic phosphorus concentrations

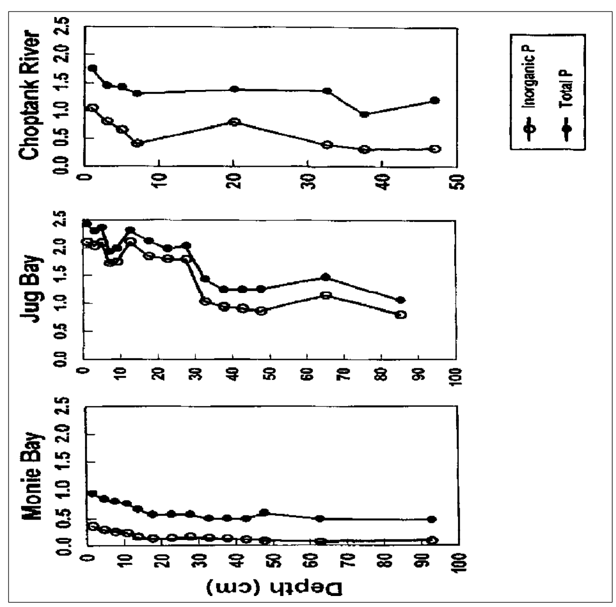

Figure 2. Depth profiles of total and inorganic phosphorus (mg g^{-1}). The Choptank River site is located at Windy Hill, an area of maximum turbidity on the river.

decrease with increasing depth of burial. Oranic phosphorus is the main phosphorus form at the Monie Bay site; the marsh appears to match sea-level rise by plant growth, rather than trapping of inorganic particulates. Cores from Jug Bay are similar to others from Patuxent River marshes (Zelenke unpublished data); these cores show a constant but small fraction of organic phosphorus. The source of phosphorus in these marshes is suspended inorganic matter from the Patuxent River drainage, The phosphorus concentrations in these sediments is strongly dominated by inorganic phosphorus, which decreases with depth. Sites along the Choptank River show relatively even distributions of organic and inorganic phosphorus throughout, with only small decreases in total phosphorus with increasing depth.

DISCUSSION

Controls on Phosphorus Distribution in Tidal Marsh Sediments

In all cores, we found a surface enrichment of phosphorus similar to that found in studies by Chambers and Odum (1990). This enrichment is most likely the result of postdepositional mobility of phosphorus as it moves with iron to the oxidized layer and precipitates with the iron oxides ($FeOOH-PO_4$). Phosphorus must be in a dissolved inorganic state (PO) to be absorbed by marsh primary producers. This would seem to indicate that organic forms of phosphorus would be more stable, and more strongly retained in sediments than would inorganic forms. However, inorganic phosphorus in the oxidized cap of sediments is strongly bound by iron, greattly reducing rates of transformation to biologically available dissolved forms. Organic storage of phosphorus depends on the growth of primary producers and the subsequent organic matter degradation, which can be limited by any number of factors (ie, nitrogen availability, solar radiation). If the overall storage capacities of tidal marsh sediments are to be determined, the difference between these two mechanisms of storage must be more clearly understood.

High variability in phosphorus forms has been observed in different marshes. Jug Bay sediments store mostly inorganic phosphorus. This is attributable to a combination of factors, including the high particulate load in the Patuxent River, and the export of much of the plant biomass during the winter months. Monie Bay phosphorus storage is mostly in an organic form, resulting from the low particulate inputs and the year-round presence of *Spartina alternifora.*

Fluxes of Phosphorus to Marsh Sediments

Early estimates of phosphorus burial in Monie Bay show that it does not play a significant role in the retention of phosphorus. Preliminary calculations show that only 0.27 g P m^{-1} y^{-1}, is buried, whereas a typical subtidal sediment of the Chesapeake Bay may retain 1.0 g P m^{-1} y^{-1} (Boynton et al. 1994). However, a study of marshes along the Choptank River found that the marshes retained more phosphorus than did the subtidal sediments, as shown in (figure 3) (Stevenson 1991). This contradiction exemplifies how little is known about the retention of phosphorus by marsh sediments. Early analyses of Jug Bay sediments indicate that accretion rates may be as high as several centimeters per year. Jug Bay marsh sediments are likely to provide important nutrient buffering in the Patuxent River. Management of tidal marsh ecosystems is becoming increasingly critical to their maintenance in Chesapeake Bay. Increasing our understanding of the relative importance of these systems will help ensure their proper management, Studies such as this one hope

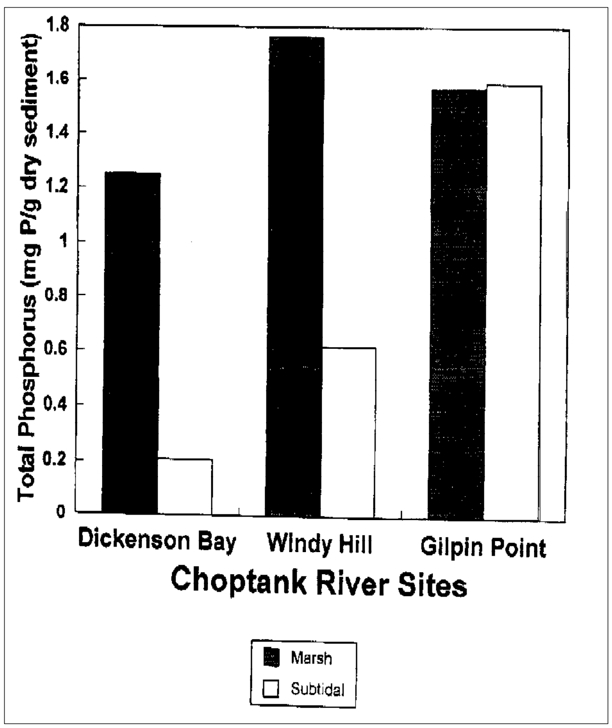

Figure 3. Choptank River phosphorus burial. Dickinson Bay is located

to clarify and quantify the role of tidal marsh ecosystems such as Jug Bay, Monie Bay, and Otter Creek in the phosphorus budget of the Chesapeake Bay.

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Toward a Sustainable Coastal Watershed:
The Chesapeake Experiment. Proceedings of a Conference
1-3 June 1994. Norfolk, VA
Chesapeake Research Consortium Publication No. 149

Temporal and Spatial Trends of Benthic Sulfate Reduction along the Chesapeake Bay Estuarine Gradient

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Abstract: As part of the ongoing Chesapeake Bay Land Margin Ecosystem Research (LMER) project, we investigated factors controlling both temporal and spatial trends of benthic sulfate reduction (SR). Three stations (upper [UB], mid [MB], and lower bay [LB]) along the north to south (< 0.1-30 ppt) salinity gradient were monitored from early spring through late fall during 1989-93. These sites respectively represented clay, organic/silt, and sand-dominated benthic regimes, common in the Bay. Temperature was the primary within-site control influencing seasonal trends in SR. Within-site interannual variations in SR may be influenced by yearly differences in the duration and intensity of spring river flow. Specifically, an exceptionally large 1993 spring freshette, and subsequent enhanced loading of organic and inorganic matter to the benthos, may have been responsible for a 1993 summer SR rate ten times that previously observed at the UB site.

Spatial trends in SR were controlled primarily by the between-site spatial variation in the quality and quantity of sedimentary organic carbon. Temporal within-site changes in the quality and quantity of surficial sediment (top 2-3 mm) organic carbon were generally not statistically significant. The average annually integrated (12 cm) areal SR rates were 1.0, 7.8, 5.2 mol $SO_4^{-2}*m^{-2}*yr^{-1}$ for UB, MB ,and LB, respectively. Rates of SR were concluded to be C and/or SO_4^{-2} limited in the UB, SO_4^{-2} limited at depth in the MB, and C limited in the LB.

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THE LONG-TERM FATE OF ANTHROPOGENIC PHOSPHORUS IN THE CHESAPEAKE BAY: WHERE IS IT?

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Abstract: Recent studies have indicated that the primary output term for phosphorus mass balances in Chesapeake Bay is the burial of phosphorus in sediments. Phosphorus is not exported to the coastal ocean, but rather is imported into the southern part of the Bay. Examination of phosphorus concentrations across the estuarine salinity gradient shows a modest enrichment of sediment phosphorus concentrations in the upper Bay, but overall concentrations are similar throughout the central axis of the Bay. We have examined the burial fluxes and sediment-water exchange of phosphorus in several parts of the Chesapeake Bay and have found that the mid-bay region is highest in phosphorus recyling and lowest in phosphorus burial. Data from ^{210}Pb-dated cores indicate that phosphorus deposition in the mid-Bay region has not changed during the 20th century, despite a large increase in phosphorus loading rates. The fate of most anthropogenic phosphorus in Chesapeake Bay is deposition in the terrestrially dominated environments of the upper Bay and subestuaries. Such environments are highly retentive of phosphorus because the water column is oxygenated and there is an abundance of phosphorus-adsorbing iron oxide minerals.