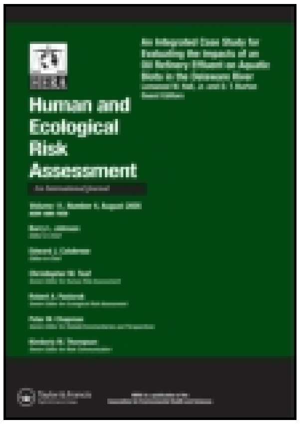


Human and Ecological Risk Assessment: An International Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/bher20

Outline of A New Approach to Evaluate Ecological Integrity of Salt Marshes

Cathleen Wigand [a], Randy Comeleo [b], Richard McKinney [a], Glen Thursby [a], Marnita Chintala [a] & Micheal charpentier [c]

[a] EPA, National Health and Environmental Effects Research Laboratory, 27 Tarzwell Drive, Narragansett, RI 02882

[b] OAO Corporation, 200 Southwest 35th Street, Corvallis, Oregon 97333

[c] OAO Corporation, 27 Tarzwell Drive, Narragansett, RI 02882

Version of record first published: 03 Oct 2012.

To cite this article: Cathleen Wigand, Randy Comeleo, Richard McKinney, Glen Thursby, Marnita Chintala & Micheal charpentier (1999): Outline of A New Approach to Evaluate Ecological Integrity of Salt Marshes, Human and Ecological Risk Assessment: An International Journal, 5:7, 1541-1554

To link to this article: http://dx.doi.org/10.1080/20018091095177

Human and Ecological Risk Assessment: Vol. 7, No. 5, pp. 1541-1554 (2001)

Outline of A New Approach to Evaluate Ecological Integrity of Salt Marshes

Cathleen Wigand,[1*] Randy Comeleo,[2] Richard McKinney,[1] Glen Thursby,[1] Marnita Chintala,[1] and Michael Charpentier[3]
[1]US EPA, National Health and Environmental Effects Research Laboratory, 27 Tarzwell Drive, Narragansett, RI 02882. [2]OAO Corporation, 200 Southwest 35th Street, Corvallis, Oregon 97333. [3]OAO Corporation, 27 Tarzwell Drive, Narragansett, RI 02882

ABSTRACT

The integrity of coastal salt marshes can be determined from the extent to which they provide key ecosystem services: food and habitat for fish and wildlife, good water quality, erosion and flood control, and recreation and cultural use. An outline of a new approach for linking ecosystem services with metrics of structure and function to evaluate the ecological integrity of salt marshes is described. One main objective of the approach is to determine whether differences in structure and function can be detected among salt marshes with similar geomorphology and hydrology but different degrees of anthropogenic stress. The approach is currently being applied to salt marshes of Narragansett Bay, RI, USA. Stable nitrogen isotopic ratios of the marsh biota reflected the nitrogen sources from the adjacent watersheds and were significantly correlated with percent residential land use. Results show that plant zonation significantly ($r = -0.82$; $p < 0.05$) relates with percent residential land use and is potentially a sensitive indicator of anthropogenic disturbance of New England salt marshes. We are currently examining species diversity, denitrification rates, and susceptibility to erosion among the sites for additional indicators of salt marsh condition. Our results to date suggest that this approach will provide the methods needed for managers to systematically monitor and evaluate the integrity of salt marshes.

Key Words: ecosystem services, habitat, water quality, salt marsh, plant zonation, integrity.

INTRODUCTION

Evaluating the overall health of an estuary requires understanding the integrity of its components such as coastal salt marshes, seagrass beds, and tidal and subtidal

* Corresponding author: wigand.cathleen@epamail.epa.gov

1080-7039/01/$.50

flats. We describe an approach to evaluate the integrity of the first of these key estuarine habitats, the salt marshes. In this new approach, ecological indicators of the goods and services that marshes provide are described by a suite of structural and functional metrics. Comparing salt marshes with similar hydrology and geomorphology but different anthropogenic stress will allow for developing a reference system of salt marsh integrity, ranging from least disturbed to most disturbed. This type of classification system to evaluate salt marsh condition has been sought by managers, regulators, and restoration specialists for more than 25 years (Oviatt *et al.* 1977).

The integrity of coastal salt marshes can be determined from the extent to which they provide five services: providing habitat for wildlife, maintaining good water quality, producing food, controlling erosion and flooding, and providing recreation and cultural use (Costanza *et al.* 1997). These services represent the direct and indirect benefits of salt marshes to society. Although some of them historically have been included in benefit assessments because they yield commodities with clear monetary value (*e.g.*, oysters, clams, shrimp, fish produced) or because they are desired and used by society (*e.g.*, recreation), other services like providing habitat for wildlife, controlling erosion, and maintaining water quality are often neglected because they do not have direct market value or are difficult to quantify (Stevens *et al.* 1995; USEPA 2000). The U.S. Environmental Protection Agency, however, recognizes the importance of these nonmarket benefits and the ability to identify and evaluate them (USEPA 2000). Indicators of salt marsh services, and thus of integrity, can be developed from the structural and functional elements of the marsh (Figure 1).

Because it is not feasible to measure all the biotic and abiotic components of a system and their interrelationships, metrics linked to specific ecosystem services or values have been recommended within the framework of ecosystem assessment (Nip and Udo de Haes 1995; Lemly and Richardson 1997). Suites of metrics are also used in following the recovery of ecosystems from disturbances (Kelly and Harwell 1990). Metrics of structure and function for use in indicators of salt marsh integrity were selected by the following criteria (Meyer 1997):

1. Use a suite of metrics rather than a single one;

2. Look for integrators of function by examining the structure of the food web, chief geochemical processes, productivity, physiological or reproductive function in key species, the base of the food web, chief biological processes (*e.g.*, nutrient cycling; mineralization; microbial activity), and chief abiotic regulators (*e.g.*, temperature, hydrodynamics) and biotic regulators (*e.g.*, keystone species);

3. Expect the unexpected because disturbances are a natural part of systems.

Some metrics of structure and function currently being quantified in salt marshes of Narragansett Bay are listed in Figure 1. There are many metrics that could be quantified, but it is important to choose those that will best link with the indicators of ecosystem services that are of interest to the stakeholders involved in the analysis.

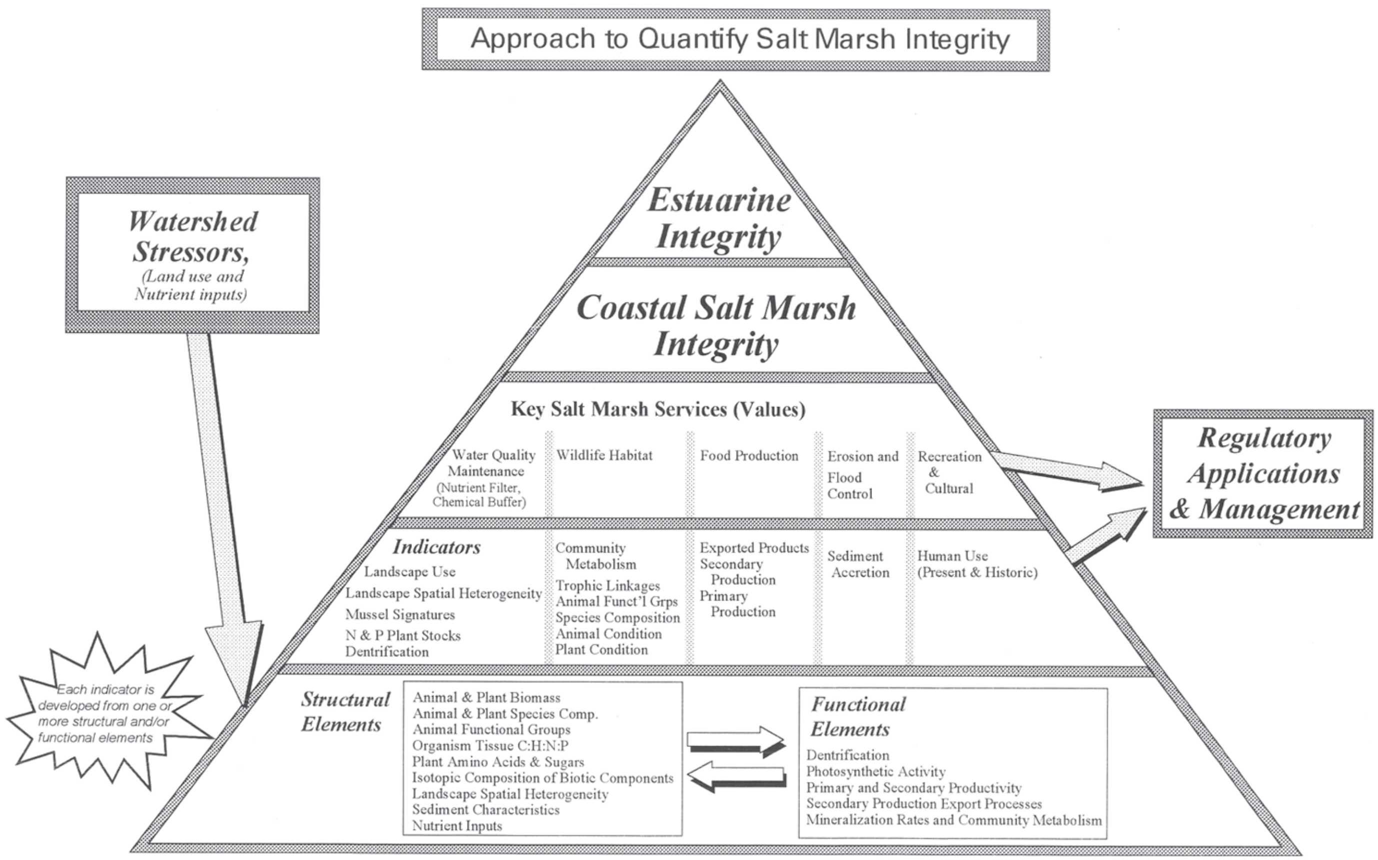


Figure 1. **Outline of the approach to evaluate salt marsh integrity based on quantification of indicators linked to key salt marsh services.**

In our approach, land use practices and the resulting human-accelerated environmental changes (*e.g.*, eutrophication, erosional processes) are coupled with measurements of structure and function in a number of coastal salt marshes. An anthropogenic gradient will be formulated from evaluating development (*i.e.*, percent residential, agricultural, industrial) in the watersheds adjoining the salt marshes and choosing a subset of sites that represent from low to high human activity. The spatial ranges of stressors and effects will substitute for temporal changes when evaluating the effect of human activities (Pickett 1988). Therefore, by examining a number of marshes receiving varying levels of similar stressors at the same time, we can substitute space for time to evaluate effects of human activities on marsh integrity. Valiela *et al.* (1992) described a similar approach, coupling watershed patterns with structure and function, to evaluate subtidal habitats in Waquoit Bay, MA. The Waquoit Bay research suggested that attention must be given to watershed land use practices when considering the condition of key estuarine habitats due to the elevated nitrogen loading (primarily from human activities) to the systems (McClelland *et al.* 1997; Valiela *et al.* 1997; McClelland and Valiela 1998).

The approach based on watershed units will provide a presumed gradient with wetland clusters of low, medium, and high human alteration. Following the premise of Brinson's hydrogeomorphic model (1993) for comparing wetlands and conducting functional assessments of systems, all sub-estuaries with adjoining salt marshes to be studied should have the same sedimentary bedrock. To minimize variations in hydrodynamics among the coastal salt marshes, all sites should have similar tidal range, mouth diameter, and water depth.

We hypothesize that coastal salt marshes in watersheds with increased human activity and urbanization will have distinct structural and functional signals that can be used to develop indicators of salt marsh services. This survey approach will preserve those measures of structure and function that describe declines in ecosystem services with increases in anthropogenic influence. The integrity indicators will then be developed from those metrics.

The general steps in the outline of the approach are listed below.

1. Describe and quantify the structure and function in a group of salt marshes with similar geomorphology and hydrology but different degrees of anthropogenic stress. Determine if there are significant differences in structure and function among marshes receiving varying anthropogenic stress.

2. If yes, can the differences in structure and function be related to the degree of anthropogenic stress?

3. If yes, can the differences in structure and function be related to differences in chief ecosystem services provided by the marshes?

4. If yes, do other marshes from the same region (and with similar geomorphology and hydrology) fit the patterns derived from the original set of salt marshes.

5. If yes, can the same relationships be found for marshes and watersheds in different regions?

At this time we are applying this approach (steps 1, 2, and 3) to the subestuaries and salt marshes of Narragansett Bay.

METHODS

The watersheds for each subestuary in Narragansett Bay were delineated using 15-min (1:24,000 scale) topographic maps from the United States Geological Survey (USGS). The watershed information was processed using the ARC/INFO software package from the Environmental Systems Research Institute (ESRI). Data layers for hydrography, digital elevation models (DEMs), and land use and land cover were obtained from the Rhode Island Geographic Information System. The layers for hydrography were derived from 1:24,000-scale USGS topographic maps. The DEMs came from USGS digital elevation models and had a resolution of 30 meters. The data layer for land use and land cover was developed from 1995 aerial photography (1:24,000 scale) coded to Anderson modified level 3 (Anderson *et al.* 1976) to one half acre minimum polygon resolution. We characterized the watersheds by the relative amounts of natural land types (forested, brushland, and inland wetland) and human-altered types (residential, agricultural, industrial and commercial, and recreational). From about 30 possible subestuaries in Narragansett Bay, we chose ten subestuaries from the main basin of Narragansett Bay that had similar geomorphology and exchange with the sea (Figure 2). We deliberately chose watersheds with no known point sources of nitrogen. Since residential lands dominated the human-altered types in this urbanized region, we used the extent of this land type in correlation analyses with various marsh metrics. Probability for significance is reported at $p < 0.05$.

Since not only the percentages of various types of land development (*e.g.*, percent residential land use), but also the location of remaining natural lands in the landscape could influence nutrient inputs, we modeled and predicted the flow of water and the percent of the flow intercepted by natural lands in the study areas with the GRID module of Arc/Info software. The terrain for each watershed was developed from its topography and hydrography, and was used to create drainage networks with cells of 30 meters square. Because GRID can sum the number of upstream cells for each cell in a drainage network, one can determine how many upstream cells are contributing to the flow in each downstream cell. By integrating the land use and land cover data layer with the drainage network, the number of upstream cells of particular land uses and land covers that contribute to the flow at a downstream location could also be determined. This method was used to quantify the flow to the sampling locations in each watershed, *i.e.*, to determine the "cell accumulation values" for the sampling sites.

In order to incorporate the effects of inland wetlands, forests, and brushlands in intercepting diffuse flow, the following procedure was developed. Our method assumes that any substantial stream flow into a forest, wetland, or brushland will be carried through the land, while more diffuse flow will be intercepted by the wetland

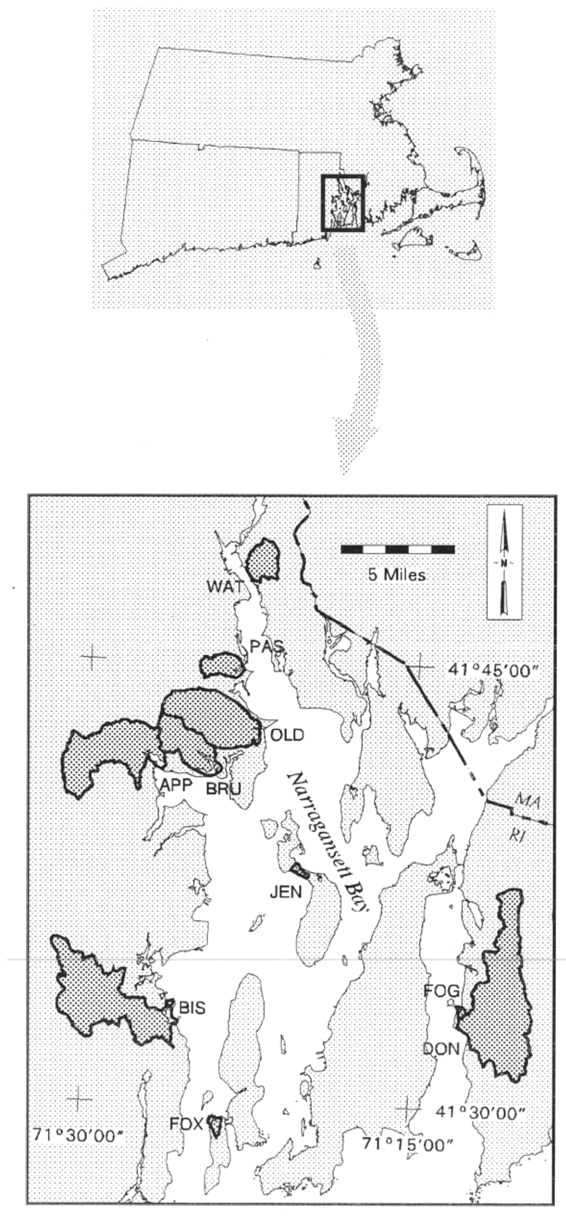


Figure 2. Location of the ten subwatershed and marsh sites in Narragansett Bay, Rhode Island, USA.

or forested area. In this coarse indicator of water transit, we do not account for nutrient exchange between the water and inland wetlands, forests, or brushlands.

To develop a criterion to describe whether flow was diffuse or not, the cell accumulation values near the headwaters of designated streams by the RIGIS database were determined for all ten watersheds. This set of designated streams had cell accumulation values ranging from 0 to 5132, with a median of 117, and were generally smaller for the smaller watersheds. Based on these data we set cell accumulation values of 100 or above as large enough to carry water through a wetland or forest, and classified each such cell as a stream. Next, the cells of this updated land use grid, which were classified as wetlands or forest, were coded such that any upstream accumulation that flowed into them (other than stream flow) was intercepted and not transferred downstream. The effect of these steps was that any cells that had an accumulation value less than 100 and which flowed into a wetland, brushland, or forest would be reset to zero, while cells that had an accumulation value of 100 or more were considered to be flowing streams. This caused wetlands, brushlands, and forested areas to act as sinks for diffuse flows, while the newly defined streams flowed through wetlands, forests, or brushlands and maintained their accumulation values. Flow accumulation values were then determined for the sampling locations within each watershed with the sinks integrated into the drainage network. Values of the percent intercepted flow were then calculated by dividing the flow accumulation values obtained using the drainage network with sinks by the flow accumulation values obtained using the drainage network without sinks (Table 1).

Total dissolved nitrogen was measured in discharge streams associated with the salt marshes in 1998 and 1999 in the spring, summer, fall, and winter (1999 only). Water samples were filtered (GF/F) in the field, transported on ice, and frozen until analysis of dissolved nitrogen. Total dissolved nitrogen (sum of nitrate, nitrite and ammonia) was measured on a Lachat Instruments QuikChem 8000 FIA+ automated ion analyzer and expressed as μM N/L. Determination of ammonia was based on the Berthelot reaction, where ammonia reacts in alkaline solution with hypochlorite to form monochloramine, which, in the presence of phenol, catalytic amounts of nitroprusside and excess hypochlorite, give indophenol blue measured at 630 nm (Diamond 1997a). Nitrate and nitrite combined are determined by passing the sample through a copperized cadmium column to reduce nitrate to nitrite and the subsequent nitrite (reduced nitrate plus original nitrite) are determined as described above (Diamond 1997b). Dissolved nitrogen concentrations were correlated with the watershed indicators (*e.g.*, percent residential land use, percent intercepted flow).

Because studies have shown that stable nitrogen isotope measurements can be used to trace nitrogen from diffuse, land-based sources to coastal marshes (McClelland *et al.* 1997; McClelland and Valiela 1998; McKinney *et al.* 2001), the nitrogen isotopic composition of the marsh plant, *Spartina alterniflora* was determined. Live plant tissue was dried at 60°C to a constant weight and then clipped into 2-cm lengths and ground on a Wiley Mill. The stable nitrogen isotopic ratio of the plant tissue was measured by continuous flow isotope ratio mass spectrometry (CF-IRMS), using a Carlo-Erba NA 1500 Series II Elemental Analyzer interfaced to a Micromass Optima Mass Spectrometer®. The stable nitrogen isotope ratio ($\delta^{15}N$) is generally expressed

Table 1. Land use types and percent intercepted flow listed from lowest to highest percent residential land use.

SITES	Land use Types				Flow Indicator
	Residential	Agricultural	Industrial and Commercial	Recreational	*Percent Intercepted Flow
Foxhill Pond	0.30%	28.07%	0.00%	0.00%	97.99%
Jenny Pond	4.00%	0.00%	0.00%	0.00%	100.00%
Mary Donavan	10.02%	19.97%	0.50%	0.13%	85.95%
Fogland	14.91%	46.16%	0.00%	0.00%	60.55%
Bissel Cove	22.06%	4.66%	1.90%	1.15%	67.33%
Apponaug Cove	43.27%	3.07%	12.27%	3.76%	41.62%
Old Mill Creek	44.46%	1.92%	7.58%	2.26%	30.61%
Watchemoket Cove	55.98%	0.00%	9.54%	13.86%	6.40%
Brush Neck Cove	61.79%	0.68%	7.14%	2.90%	10.44%
Passeonquis Cove	65.37%	0.00%	5.64%	3.78%	34.91%

[b]Percent intercepted flow is the percent of the surface water flow that is predicted to be intercepted by forests, brushlands, and inland wetlands (see text for further description).

as the ratio of the ^{15}N isotope to ^{14}N in a sample to that in a reference material ($\delta^{15}N = (^{15}N/\ ^{14}N_{sample}) / (^{15}N/\ ^{14}N_{standard}) - 1 \times 1000$ ‰) and is reported in parts per thousand or per mille (‰) (Mariotti 1983). All samples were analyzed in duplicate with a typical difference of about 0.3 ‰.

In the field, the plant zonation on the marsh landscape was examined at the ten sites in 1998 and 1999. The width of each marsh was approximated by pacing the edge by foot. Three transects were set equidistant from the upland edge (*i.e.*, beginning at the wooded edge) and ran perpendicular to the cove edge. The number of zones (of at least one meter in length) was determined by the number of times the plant species composition of a discrete area changed (*e.g.*, from *S. patens* to short *S. alterniflora* or to mixed *S. patens — Distichlis spicata*) along the transect. For each site, the average number of plant zones was determined each year as the average of the three transects and these values were correlated with the watershed indicators.

RESULTS

A GIS analysis showed that average residential land use in the watersheds of the ten marshes ranged from 0.3 to 65% (Table 1). The percent agricultural land use was similar among most sites and ranged from 0 to 28 percent except for Fogland (Table 1). Along the percent residential gradient there is a pattern of low, medium, and high total dissolved nitrogen concentrations associated with the discharge streams except for Fogland where the greatest percent agricultural land use was reported (Table 2). Across all ten sites there are significant relationships between total dissolved nitrogen and the watershed indicators in the summer and fall (Table 3). However, when Fogland is removed from the correlation analyses, the relationships between total dissolved

Table 2. Seasonal total dissolved nitrogen for 1998 and 1999 in discharge streams associated with the marsh sites. For each year two samples were averaged at each site. nd = no data

SITES	Total Dissolved Nitrogen (uM)						
	1998			1999			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Foxhill Pond	3.86	19.01	39.52	16.84	12.07	nd	nd
Jenny Pond	30.39	3.90	6.50	23.52	5.28	3.18	nd
Mary Donavan	15.93	21.13	8.16	24.54	18.09	2.47	7.15
Fogland	889.42	478.78	18.87	605.54	527.17	nd	nd
Bissel Cove	66.31	43.66	30.39	67.01	45.47	13.92	11.63
Apponaug Cove	126.24	96.59	75.62	33.11	100.18	20.50	16.58
Old Mill Creek	207.00	149.19	78.40	99.53	149.47	54.59	43.94
Watchemoket Cove	296.70	275.33	307.06	338.74	354.24	183.28	249.51
Brush Neck Cove	445.06	307.00	373.60	313.76	330.93	125.22	161.67
Passeonquis Cove	298.99	249.20	213.20	290.26	261.52	100.87	92.08

Table 3. Relationship of watershed indicators with the average two-year (1998, 1999) total dissolved nitrogen concentrations in discharge streams of the marsh sites.

Season	All Ten Sites				Without Fogland			
	% Residential		[b]% Intercepted Flow		% Residential		[b]% Intercepted Flow	
	r	P	r	P	r	P	r	P
Spring	+0.36	0.30	-0.52	0.13	+0.93	*	-0.93	*
Summer	+0.64	*	-0.76	*	+0.89	*	-0.91	*
Fall	+0.75	*	-0.78	*	+0.74	*	-0.79	*
[a]Winter	+0.35	0.32	-0.49	0.15	+0.85	*	-0.83	*

*Probability is reported as significant when $p < 0.05$.

[a]Winter is a one-year (1999) average.

[b]Percent (%) intercepted flow is the percent of the surface water flow that is predicted to be intercepted by forests, brushlands, and inland wetlands (see text for further description).

nitrogen in the discharge streams and watershed indicators are significant for all seasons.

As we had hypothesized, the stable nitrogen isotopic ratio of the leaf tissue of *S. alterniflora* was significantly ($P< 0.05$) related (positive) to the percent residential development in the watershed (Figure 3). The average number of plant zones was negatively correlated with percent residential land use ($r = -0.82$; $p < 0.05$; Figure 4a) and related directly with the percent intercepted flow ($r = +0.80$; $p < 0.05$; Figure 4b).

DISCUSSION

Nitrogen derived from wastewater is relatively enriched in N^{15}, which results in an enriched stable nitrogen isotopic ratio in the biotic components that process the water (Kreitler *et al.* 1978; Gormley and Spalding 1979; Arevena *et al.* 1993). At the Narragansett Bay marsh sites, *S. alterniflora* (smooth cord grass) and *Geukensia demissa* (ribbed mussel) (from a concurrent study, McKinney *et al.*, 2001) showed a significant positive relationship with percent residential development. These relationships suggest that activities in the watersheds of Narragansett Bay are directly affecting the nitrogen isotopes in their biota and influencing nitrogen cycling in the marshes.

Based on the results of this study, we propose that in urbanized regions percent residential land use in watersheds adjacent to salt marshes is directly related with nitrogen loads to salt marshes. However, agricultural lands can be major sources of nutrients, and when they are present in watersheds adjacent to salt marshes, they may cause elevated nitrogen loadings as evidenced by Fogland in this study. The subwatershed associated with Fogland marsh is small (73 acres), and it primarily

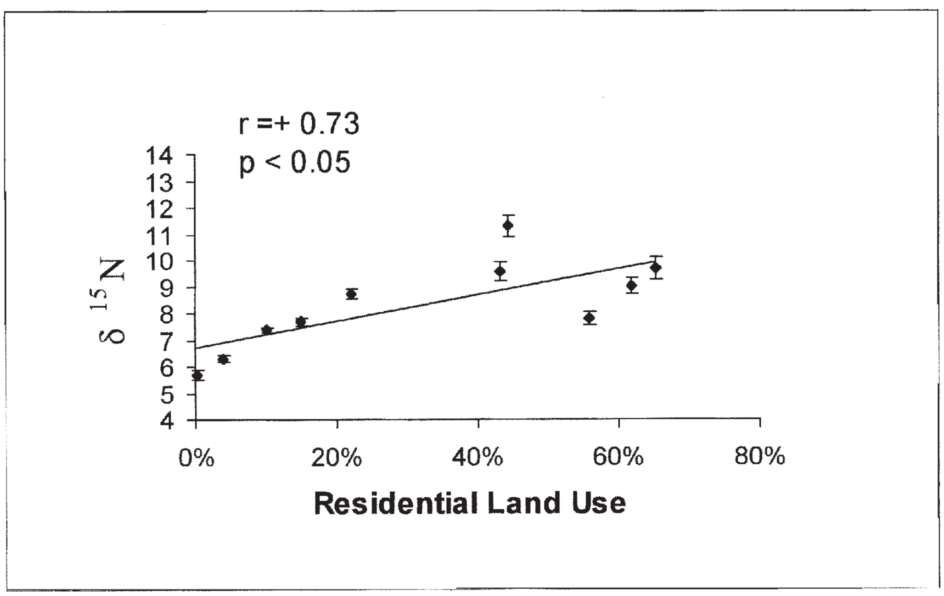
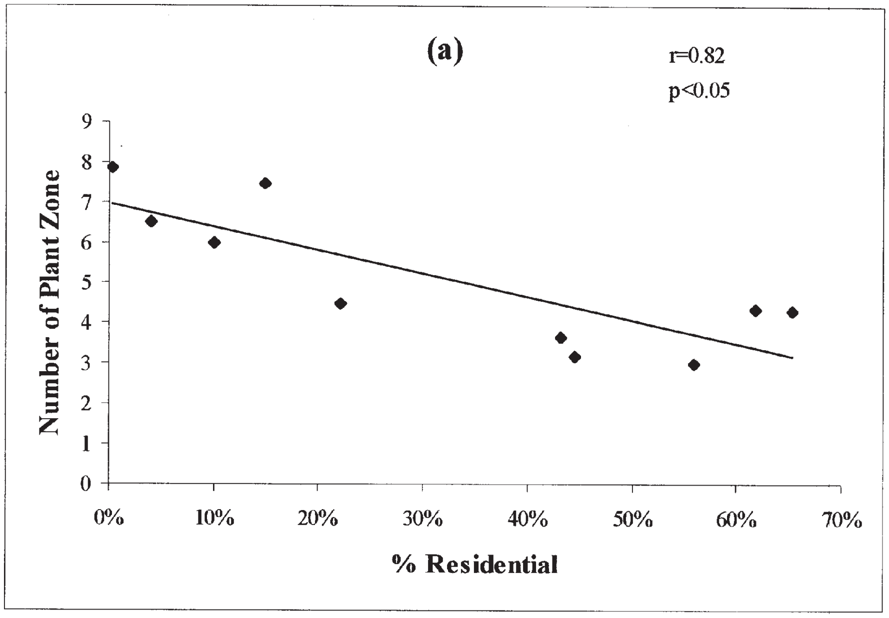


Figure 3. Relationship of percent residential land use with the stable nitrogen isotopic ratio of *Spartina alterniflora*.

200389.pgs 1550 10/12/01, 11:16 AM



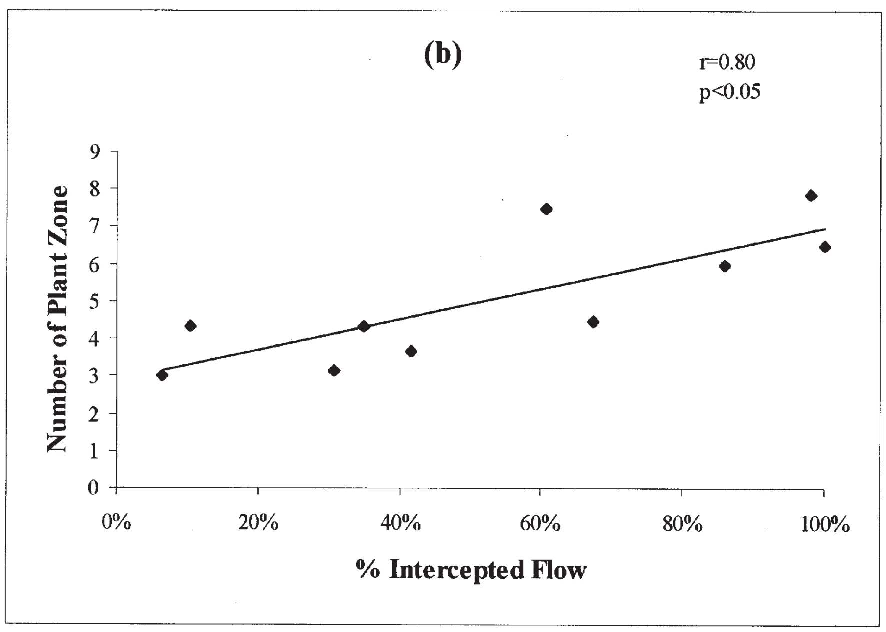


Figure 4. Relationship of the yearly (1998 and 1999) average number of plant zones on the marsh landscape with (a) the percent residential land use and (b) percent interecepted flow.

consists of a potato farm located on a hill with the marsh at the base. The groundwater and surface runoff from the farm would presumably influence the marsh study site. For the Fogland watershed and in regions where there is much agricultural development, other watershed indicators besides percent residential land use may better relate with salt marsh condition.

In geographic regions with varying human activities in watersheds adjoining coastal habitats, an indicator such as the percent intercepted flow that examines diffuse water flow through natural lands might better relate with salt marsh condition than percent residential land use. Furthermore, the protection and restoration of natural lands that are positioned in the watershed landscape to act as sinks for diffuse water flow and dissolved nutrients may have significant positive effects on marsh condition as evidenced by the relationship of the percent intercept flow indicator with the plant zonation on the marsh landscape.

A decrease in the average number of plant zones with high percent residential land use and low percent intercepted flow might be attributed to a number of indirect mechanisms including encroachment upon the high marsh due to historic filling in of marshes for development (Nixon 1982), physical disturbance by increased wrack deposition (Bertness and Ellison 1987; Valiela and Rietsma 1995), and interspecific plant competition (Levine *et al.* 1998). The low marsh *Spartina alterniflora* has been shown to be a better competitor than the high marsh *S. patens* in the presence of high nitrogen levels as would occur due to eutrophication (Levine *et al.* 1998) possibly causing a reduction in the number of plant zones and in the areal extent of some zones (*e.g.*, the *S. patens* zone) on the marsh landscape.

In addition to plant zonation, ongoing research examining animal and plant species diversity, marsh susceptibility to erosion, and denitrification rates suggests that differences in structure and function can be detected among the salt marshes and that these metrics are closely linked with ecosystem services that the salt marshes are providing. This approach provides a systematic means of developing practical indicators for managers and regulators to monitor and evaluate salt marsh integrity for restoration and protection purposes.

ACKNOWLEDGMENTS

A number of colleagues at the Atlantic Ecology Division, Narragansett R.I., contributed to the ideas and approach developed in this document including Carol Pesch, John Kiddon, and Skip Nelson and at the Institute of Ecosystem Studies, Millbrook, N.Y., Stuart Findlay. We are grateful for their contributions and insight. We thank Molly Connell for her help in conducting the field surveys. Hal Walker, Antelmo Santos, Steve Ryba, Skip Nelson, Steve Schimmel, and Wayne Munns provided final internal reviews. Ken Rahn helped with the structure of the text in the paper. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency. This is Contribution AED-00-083.

REFERENCES

Anderson JR, Hardy EE, Roach JT, *et al.* 1976. A land use and land cover classification system for use with remote sensor data. Geological Survey Professional Paper 964, A revision of the land use classification system as presented in US Geological Survey Circular 671. United States Government Printing Office, Washington, DC, USA. (Also, available at: http://mapping.usgs.gov/pub/ti/LULC/lulcpp964/lulcpp964.txt)

Aravena R, Evans L, and Cherry JA. 1993. Stable isotopes of oxygen and nitrogen in source identification of nitrate from septic systems. Ground Water 31:180-6

Bertness M.D and Ellison AM. 1987. Determinants of pattern in a New England salt marsh plant community. Ecological Monographs 57:129-147

Brinson MM. 1993. A Hydrogeomorphic Classification for Wetlands. Technical Report WRP-DE-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS, USA

Costanza R, d'Arge R, de Groot R, *et al.* 1997. The value of the world's ecosystem services and natural capital. Nature 387:253-60

Diamond DH. 1997a. Determination of ammonia in brackish or seawater by flow injection analysis colorimetry. QuikChem Method 31-107-06-1-C for Lachat Instruments. Milwaukee, WI, USA

Diamond DH. 1997b. Determination of nitrate in brackish or seawater by flow injection analysis. QuikChem Method 31-107-04-1-A for Lachat Instruments. Milwaukee, WI, USA

Gormly JR and Spalding RF. 1979. Sources and concentrations of nitrate-nitrogen in groundwater of the central Platte region, Nebraska. Ground Water 17:291-301

Kelly JR and Harwell MA. 1990. Indicators of ecosystem recovery. Environ Management 14:527-45

Kreitler CW, Ragone S, and Katz BG. 1978. $^{15}N/^{14}N$ ratios of ground water nitrate, Long Island, NY. Ground Water 16: 404 - 409

Lemly AD and Richardson CJ. 1997. Guidelines for risk assessment in wetlands. Environ Monitoring Assess 47:117-34.

Levine J M, Brewer JS, and Bertness MD. 1998. Nutrients, competition, and plant zonation in a New England salt marsh. Journal of Ecology 86:285-292

Mariotti A. 1983. Atmospheric nitrogen is a reliable standard for natural ^{15}N abundance measurements. Nature 303: 685-687.

McClelland JW and Valiela I. 1998. Linking nitrogen in estuarine producers to land-derived sources. Limnol Oceanogr 43: 577-85

McClelland JW, Valiela I, and Michener RH. 1997. Nitrogen-stable isotope signatures in estuarine food webs: A record of increasing urbanization in coastal watersheds. Limnol Oceanogr 42:930-7

McKinney RA, Nelson WG, Charpentier MA, and Wigand C. 2001. Ribbed mussel nitrogen isotope signatures reflect nitrogen sources in coastal salt marshes. Ecological Applications 11: 203 - 214

Meyer JL. 1997. Conserving ecosystem function. In: Pickett STA, Ostfeld RS, Shachak M, *et al.* (eds), The Ecological Basis of Conservation:Heterogeneity, Ecosystems, and Biodiversity, pp 136-145. Chapman and Hall, NY, NY, USA

Nip MI and Udo de Haes HA. 1995. Environmental auditing, ecosystem approaches to environmental quality assessment. Environ Manage 19:135-45

Oviatt CA, Nixon SW, and Garber J. 1977. Variation and evaluation of costal salt marshes. Environ Manage 1:201-1

Pickett STA. 1988. Space for time substitution as an alternative to long-term studies. In: GE Likens (ed), Long-term Studies in Ecology, pp 110-135. Springer-Verlag, NY, NY, USA

Stevens TH, Benin S, and Larson JS. 1995. Public attitude and economic values for wetland preservation in New England. Wetlands 15:226-31

USEPA (United States Environmental Protection Agency). 2000. Assessing the Neglected Ecological Benefits of Watershed Management Practices - A Resource Book. Assessment and Watershed Protection Division, Office of Wetlands, Oceans, and Watersheds, Washington, DC, USA

Valiela I and Rietsma CS. 1995. Disturbance of slat marsh vegetation by wrack mats in Great Sippewissett marsh. Oecologia, 102:106-112

Valiela I, Foreman K, LaMontagne M, et al. 1992. Couplings of watersheds and coastal waters: Sources and consequences of nutrient enrichment in Waquoit Bay, MA. Estuaries 15:443-57

Valiela I, Collins G, Kremer J, et al. 1997. Nitrogen loading from coastal watersheds to receiving estuaries: new method and application. Ecol Applicat 7: 358-80