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RESEARCH ARTICLE

Empirical relationships between land use/cover and estuarine condition in the Northeastern United States

Wilfrid Rodriguez · Peter V. August · Yeqiao Wang · John F. Paul · Arthur Gold · Norman Rubinstein

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Abstract Land–water interactions were examined in three regions in the Virginian Biogeographic Province; the southern shore of Cape Cod, Massachusetts; the Hudson/Raritan region of New York; and the eastern shore of the Delmarva (Delaware/Maryland/Virginia) Peninsula. Cumulative distribution functions were used to evaluate similarity in environmental condition among estuaries. Spatial-setting variables (location in a river, coastal lagoon, or in open waters) were associated with variation for some measures of estuarine condition. Patterns of coastal urban and agriculture gradients were measured and their relationship with indicators of estuarine condition was modeled statistically. When estuaries were pooled, the highest variation explained by spatial-setting variables was found for dissolved oxygen (DO, $R^2 = 0.44$) and salinity ($R^2 = 0.58$), with DO decreasing in river locations and salinity decreasing with rainfall and sampling locations near rivers. The explanatory power for the other indicator variables was low and varied from 6% to 27%. Rainfall explained some of the variation ($R^2 = 0.23$) in total suspended solids. Moderate ($0.4 < |r| < 0.7$) to strong ($|r| \geq 0.7$) linear associations were found between total urban area and measures of estuarine condition. Within regions, total urban area was positively associated with Silver ($r = 0.59$), Cadmium ($r = 0.65$), and Mercury ($r = 0.47$) in Cape Cod, and inversely related to DO ($r = -0.65$) in the Hudson/Raritan region. No associations were found in the Delmarva Peninsula study area. Total area of agriculture showed a moderate association with Arsenic in Cape Cod, but no other associations were found in the other two regions. Our analyses show a measurable impact of urban land use on coastal ecosystem condition over large areas of the northeastern United States. This pattern was most evident when many different landscapes were considered simultaneously. The relationship between urban

W. Rodriguez (✉)
Department Civil and Environmental Engineering,
University of Rhode Island, 1 Lippit Rd, Bliss Hall,
Room 308C, Kingston, RI 02881, USA
e-mail: wrg@etal.uri.edu

P. V. August · Y. Wang · A. Gold
Department of Natural Resources Science, University
of Rhode Island, Kingston, RI 02881, USA

J. F. Paul
U.S. Environmental Protection Agency, ORD,
NHEERL, Research Triangle Park, NC 27711, USA

N. Rubinstein
U.S. Environmental Protection Agency, Atlantic
Ecology Division, Narragansett, RI 02882, USA

W. Rodriguez
Smithsonian Environmental Research Center, 647
Contees Wharf Road, Edgewater, MD 21037, USA

development and estuarine condition were weaker within the individual regions studied. The use of land use/cover models for predicting estuarine condition is a challenging task that warrants enhancements in the type, quantity, and quality of data to improve our ability to discern relationships between anthropogenic activities on land and the condition of coastal environments.

Keywords Landscape analysis · Estuarine condition · Water quality · GIS

Introduction

The Virginian Biogeographic Province (Fig. 1a), which extends from Cape Henry Virginia, at the mouth of the Chesapeake Bay to Cape Cod, Massachusetts in the northeastern United States contains more than 23,573 km^2 of estuarine waters and includes a number of national wildlife sanctuaries and national parks (Paul et al. 1999; NPS 2000; NCCR 2001). The high urbanization and intensive agricultural practices in these areas (USEPA 1995; Roman et al. 2000; NCCR 2001; Howarth et al. 2002) are the main cause of human-induced eutrophication and sediment contamination of estuarine waters (Nixon 1995; Valiela et al. 1992; O'Connor 1996; Malone and Conley 1996; Hobbie 2000; Evgenidou and Valiela 2002). Anthropogenic pressures are driving factors leading to changes in ecosystem structure and function (Valiela 1995; Smith 1998), soil and water quality, biodiversity, and global climate (Houghton 1994; Turner et al. 1995; August et al. 2002).

Human activities have changed nutrient cycling in terrestrial ecosystems, accelerating their delivery to coastal waters (Howarth et al. 1996; Vitousek et al. 1997; Anderson et al. 2002; Boyer et al. 2002; Howarth et al. 2002), and causing nutrient over-enrichment, the principal cause of eutrophication in estuarine waters (Nixon 1995; NRC 2000; Hobbie 2000; Evgenidou and Valiela 2002). As municipal wastewater treatment continues to improve, most of these nutrients, especially nitrogen, increasingly come from diffuse sources, such as agriculture and atmospheric deposition (Howarth et al. 1996; Smith 1998; Castro et al. 2001; Paerl et al. 2002), and urbanization (Boyer et al. 2002; Wang et al. 2003).

The Environmental Monitoring and Assessment Program (EMAP) (USEPA 1990) and the Mid-Atlantic Integrated Assessment (MAIA-Estuaries) (Kiddon et al. 2003) evaluation of ecological condition of coastal ecosystems in several biogeographic regions of the United States have been the first step towards the development of a comprehensive, national-scale approach to monitoring, with an ultimate application to management and conservation of estuarine resources. However, the need to quantify relationships between land use/cover factors and estuarine condition continues to be of vital importance for the development of applied models that can predict degradation of environmental quality in estuaries under different land use development scenarios. We hypothesize that (1) coastal land use/cover gradients and their spatial patterns in the landscape are forcing variables that determine water quality condition as measured by regional monitoring programs such as EMAP; (2) spatial arrangement (i.e., location in relation to the mainland) of monitoring stations in the estuarine environment is a crucial determinant of design sensitivity to capture water quality conditions; and (3) rain events prior to measurements of water quality will confound results from monitoring stations.

Our objective is to model land–water interactions along a land use gradient in three regions in the Virginian Biogeographic Province. We used estuarine water quality data from EMAP (Weisberg et al. 1992; Paul et al. 1999) and the 1992 National Land Cover Dataset (Loveland et al. 1991; Loveland and Shaw 1996; Vogelman et al. 2001; Yang et al. 2001; Hollister et al. 2004) within a geographic information system (GIS) to quantify patterns of water quality and land use/cover. The research questions we ask in this study are the following:

1. Are measures of estuarine water quality the same among the three study regions?
2. Are spatial-setting and intense rainfall important in accounting for variation in water quality measures?

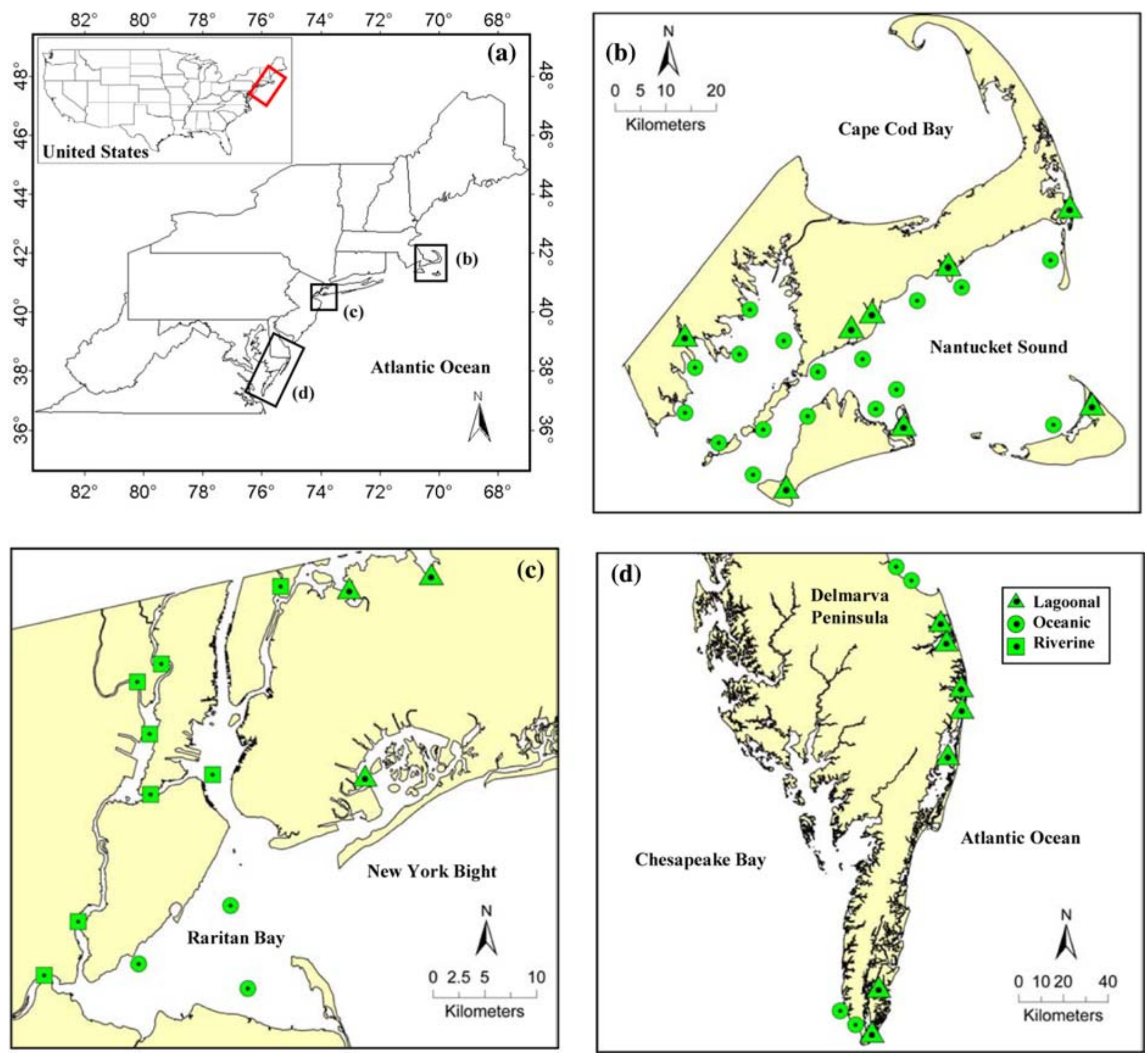

Fig. 1 Coastal areas of Cape Cod (**b**), Hudson/Raritan (**c**), and eastern Delmarva (**d**) were chosen as study areas reflecting a significant landscape gradient of agriculture and urbanization in the Virginian Biogeographic Province (**a**). Monitoring sampling stations from the 1990–1993 USEPA Environmental Monitoring and Assessment Program (EMAP) are shown based on their spatial-setting in the estuarine system (i.e., riverine, lagoonal, oceanic)

3. What is the relationship between patterns of land use/cover and estuarine condition in the Cape Cod, Hudson/Raritan, and Delmarva study regions?

Data and methods

Study areas

Three regions were chosen across the Virginian Biogeographic Province in the Atlantic seaboard of the United States (Fig. 1). They are: (1) the southern shore of Cape Cod, Massachusetts; (2) the Hudson/Raritan region, New York; and (3) the eastern shore of the Delmarva (Delaware/Maryland/Virginia) Peninsula. The criteria to choose these regions was based on: (1) large differences in degree and type of land use/cover disturbance along their coastal zones; specifically, a distinct urbanization and agricultural gradients; (2) different geomorphological and hydrological settings between the two northeastern regions

(Cape Cod and Hudson/Raritan) and the Mid-Atlantic Delmarva region; and (3) differences in tidal currents and fresh water sources. For example the Hudson/Raritan has freshwater inputs from the Hudson River and is a highly stratified system, Cape Cod is mostly fed from groundwater sources and is tidally driven. The Delmarva region contains small river inputs into Rehoboth and Chincoteague Bays and has slow residence times. Roman et al. (2000) provides an overview of watershed geology, land use history, and tidal range for the North Atlantic estuaries, including Cape Cod and Hudson/Raritan regions used in this study. Delmarva is part of the Mid-Atlantic coastal plain and consists of a flat plain with many swampy and marshy areas (USEPA 1997).

The Cape Cod region (Fig. 1b) contained 25 EMAP stations (eight within a coastal lagoon and 17 in open water). This region represented medium levels of urbanization and agricultural land uses in this study. The geology of the peninsula consists of glacially deposited sediments that extend from the coast of Massachusetts in southeastern New England (Strahler 1966). The outer portion of Cape Cod's seashore has a prominent barrier beach backed by glacial sands and gravels. This part of the peninsula contains a variety of fresh and estuarine water bodies that drain toward Cape Cod Bay. Non-point sources and their impacts on groundwater quality have increased in the area as a result of increased population growth and its exclusive dependence on local groundwater for drinking purposes (Burroughs 1993; Valiela et al. 1992; Short and Burdick 1996; Portnoy et al. 1998). The compound effect of these sources has been studied for five estuarine water bodies in or adjacent to the National Seashore (Burroughs and Lee 1991). In several instances, housing developments, solid waste disposal sites, and runoff in or adjacent to the Cape Cod National Seashore (CACO) have been identified as potential sources of eutrophication. CACO contains approximately 17,442 ha of uplands, wetlands and tidal lands located on Outer Cape Cod, Massachusetts. This area has a wide diversity of aquatic and marine habitats, such as kettle ponds, cedar swamps, vernal pools, drowned river valley salt marshes, back barrier salt marshes, barrier spits and inter-tidal mudflats (Stevens and Milstead 2002).

The Hudson/Raritan region (Fig. 1c) contained 15 EMAP stations (four within a coastal lagoon, two in open water, and eight within a river). This region represented a landscape characterized by high urbanization and low agricultural land use. This region is located in the lower Hudson–Raritan system, which includes New York Harbor. The Hudson River is the major source of freshwater input into this complex coastal plain estuary made up of tidal straits, open and enclosed bays (Raritan, Jamaica, and New York), tidal mud flats, and beaches (O'Shea and Brosnan 2000). Areas of concern for excess eutrophication, as evidenced by frequent hypoxia (dissolved oxygen [DO] < 5.0 mg l^{-1}), include Jamaica Bay, Raritan Bay, Sandy Hook, and the New York Bight Apex (USEPA 1996; O'Shea and Brosnan 2000). The Gateway National Recreation Area is located within New York Harbor estuary and is next to one of the largest metropolitan areas of the world. It is comprised of more than 105 km^2 and contains historical forts, salt marshes, and sandy beaches.

The Delmarva region (Fig. 1d) contained 11 EMAP stations (seven within a coastal lagoon, four in open water). Stations in open waters are clustered in the north and south of the Peninsula, while lagoonal stations are located in confined estuaries in the middle and upper sections of the eastern shore of the Peninsula. This region had a landscape of low urbanization and high agricultural land and is part of the coastal plain of the Mid-Atlantic region. The Delmarva coastal bays and estuaries are associated with lowland areas and soils with very low hydraulic conductivity. They are considered the least degraded of the systems in the Virginian Biogeographic region (USEPA 1997; USEPA 1998), even though they have a history of eutrophication as a result of nutrient inputs from agriculture, nutrient-rich groundwater, and sewage treatment plants (Price 1998). In addition, land development over the next 25 years has the potential to intensify the deterioration of estuarine waters in the different areas making up national parks in the area (Stevens and Milstead 2002). Assateague Island National

Seashore (ASIS) extends 190 km^2 with over half the area composed of oceanic and estuarine waters surrounding the Island.

Estuarine data

We extracted data from the Environmental Monitoring and Assessment Program (EMAP: 1990–1993) for water quality and physical characteristics of the estuarine systems located in the three selected regions. The sampling period for these data ranged from late July through August (1990–1993) because dissolved oxygen is at its lowest annual value, contaminant exposure is greatest, and living resources are most abundant (Weisberg 1992). The EMAP protocol for selection of sampling sites for large and small estuaries as well as for tidal river systems in the Biogeographic Virginian Province was based on a probabilistic design (Overton 1989; Overton et al. 1990). For detailed information on sampling design, methods, and collection of EMAP data see Weisberg et al. (1992). We divided EMAP estuarine data into four groups of indicators of estuarine condition (Table 1). The Benthic Index (BI) was used as a ‘‘biological measure’’ of the effects of indicators of eutrophication, sediment metals and organics, physical characteristics of the estuarine system, and land use effects in Cape Cod, Hudson/Raritan, and Delmarva regions. Paul et al. (1999, 2001) have done a thorough analysis and validation of this index.

In addition to EMAP's estuarine data, we retrieved rainfall data coinciding with 1990–1993 EMAP sampling periods. Rainfall is an important transport mechanism that influences the movement of nutrients and sediments to coastal marine habitats. Rain events exceeding 5.8 cm in the week prior to sampling were of particular interest since they represent storm events that would create high amounts of runoff and increase nutrient and sediment inputs into estuarine systems, thus masking a portion of the variation in dissolved oxygen and total suspended solids, as well as changes in salinity. Rainfall data from stations surrounding study sites were extracted from the National Climate Data Center to calculate total rainfall for the week prior to each EMAP sampling date.

Table 1 Estuarine data extracted from the USEPA Environmental Monitoring and Assessment Program (EMAP), measured from 1990 to 1993

Indicator group	Indicator variable	Units
Biological response	Benthic index (BI)	Unitless
Eutrophication	Surface dissolved oxygen (SDO)	mg l^{-1}
	Bottom dissolved oxygen (BDO)	mg l^{-1}
	Total suspended solids (TSS)	mg l^{-1}
	Total organic carbon (TOC)	mg l^{-1}
Sediments	Arsenic (As)	ug g^{-1}
	Cadmium (Cd)	ug g^{-1}
	Mercury (Hg)	ug g^{-1}
	Silver (Ag)	ug g^{-1}
	Fluorant	ng g^{-1}
	PAHs	ng g^{-1}
Physical Characteristics	Water depth	m
	Estuarine area	square km
	Surface salinity	ppt
	Bottom salinity	ppt
	Surface temperature	°C
	Bottom temperature	°C

Land use land cover

We chose the total amount of land cover types as the simplest metric to characterize landscape structure of the coastal zones in our study areas. Areas of different land uses were obtained from the 1992 National Land Cover Data set (Loveland et al. 1991; Loveland and Shaw 1996; Vogelman and Wickham 2000; Vogelman et al. 2001) encompassing the three regions in the study. We reclassified the 1992 NLCD from 21 classes into three general categories, URBAN, AGRICULTURE, and OTHER. The URBAN and AGRICULTURE classes were used in the statistical analyses.

Research by Comeleo et al. (1996) has shown a link between the contamination of sediments of 25 sub-estuaries from the Chesapeake Bay and the land cover of slopes by heavy metals and organic pollutants. The results indicate that urban development has an effect on the pollutant level in sediments. The effects were more marked when the sources of stress were located less than 10-km from the estuary. Based on the assumption that similar effects may be possible over three regions we used 10-km buffer distances to do a preliminary neighborhood analysis to assess the maximum spatial extent of urban and agriculture land use around EMAP stations. Results from this analysis indicated that the greatest extent of URBAN and AGRICULTURE land use/cover classes were found within 2–4 km from EMAP stations (Rodriguez 2003). In this study, a 4 km radius was used around EPA sampling stations to examine land use patterns. The amount of land use in this 4 km buffer is called ‘‘effective land use.’’ EMAP stations located further than 4 km from the shoreline were not considered in the present analysis. Assessments of the impact of land cover patterns beyond 4-km from sampling stations is provided in Rodriguez (2003).

Spatial-setting variables

The relationship between spatial-setting and indicators of water quality was modeled using three factors: (1) distance to shore (Dist_shore), (2) distance to closest river-mouth (Dist_river), and (3) spatial-setting of station in the marine environment. Spatial-setting consisted of three categories: (a) lagoonal for stations located within coastal lagoons, (b) riverine for stations within rivers, and (c) oceanic for stations located in open coastal waters. This stratification follows closely Fairbridge (1980) definition of estuarine physical divisions based on tidal action and freshwater inputs. Distance to the closest point of shore was computed with the Arc/Info (Environmental Systems Research Institute, Redlands, CA) function NEAR. Distance to river-mouth was calculated with ArcView software (Version 3.3, Environmental Systems Research Institute, Redlands, CA). In instances where more than one river was nearby, we made a choice based on which discharge point had the shortest flow path based on tidal flux and currents. Stations located inside a river were given a ‘‘Dist_river’’ value of zero.

Statistical methods

Cumulative distribution functions (CDFs) of raw data were used to visualize and test if eutrophication and sediment indicators were the same among study sites. The CDFs showed the proportion of an estuarine area at or below chosen levels of a measured indicator. CDFs also show central tendency and variation in a graphical format (Ott 1995). We tested for differences among CDFs with the Smirnov test (Smirnov 1939). This is a two-sample version of the Kolmogorov test, which is also called the Kolmogorov–Smirnov two-sample test (Conover 1999).

Linear relationships between ‘‘effective land use’’ and estuarine indicators were estimated using Pearson Product Moment correlations. Linear multiple stepwise regressions were used to select which independent variables made contributions to the overall prediction of estuarine condition. The test of significance (*F*-test) from the multiple regression determined whether the relationship between the set of independent variables and dependent variables was large enough to be measurable. All regression analyses were done with SPSS for windows version 14.0 (SPSS 2006). All geospatial analyses were performed using Arc/Info software version 8.x and ArcGIS 9.1 (Environmental Systems Research Institute, Redlands, CA).

Results

Coastal land use/cover gradient

The three study regions showed clear differences in the percentages of developed (e.g., low, high residential, and industrial landuse classes) and undeveloped areas among Hudson/Raritan, Cape Cod, and Delmarva regions. High urbanization and low agriculture characterized the Hudson/Raritan site. High agriculture and low urbanization was found in the Delmarva site. Moderate levels of development typified the Cape Cod region.

Estuarine condition

Benthic Index (BI) was lower in the Hudson/Raritan site than in the other two regions. Dissolved oxygen (DO) was similar in all three regions and suspended solids (TSS) had the highest values in Delmarva (Fig. 2a). The Hudson/Raritan region contained the highest mean values in sediment metals (Fig. 2b) and in sediment organics (Fig. 2c). Rainfall was higher in Delmarva than in the other two sites (Fig. 2d). Sampling stations in Cape were located farthest from river systems compared to Hudson/Raritan and Delmarva (Fig. 2d). URBAN land use was most extensive in the Hudson/Raritan, followed by Cape Cod, and with the lowest average in Delmarva (Fig. 2e).

Cumulative distribution functions (CDFs) for estuarine indicators differed among study regions (Fig. 3). Approximately 25% of bottom waters in the Hudson/Raritan region were below the critical 5 mg l^{-1} threshold of dissolved oxygen (Paul et al. 1998). All sampling stations in Cape Cod and Delmarva were above this threshold (Fig. 3a). CDFs for total suspended solids (TSS) showed Cape Cod with approximately 38% of areas below the 15 mg l^{-1} threshold (Dennison et al. 1993), Delmarva with 15%, and Hudson/Raritan with 55% (Fig. 3b). CDFs for total organic carbon (TOC) showed Hudson/Raritan with 38% of estuarine area with TOC concentrations approximating ≤ 2 ug g^{-1}. TOC concentrations for Cape Cod and Delmarva were not greater than 0.5 ug g^{-1}. CDFs for sediment contamination of metals and organics also showed the Hudson/Raritan region had high levels of silver, arsenic, cadmium, mercury, fluoran, and PAHs compared to Cape Cod and Delmarva (Rodriguez 2003). Statistical tests of the cumulative distributions functions showed two significant responses: (a) the highly industrialized Hudson/Raritan region differed consistently from the less industrialized regions, and (b) estuarine condition variables did not differ between Cape Cod and Delmarva regions.

Spatial-setting effect

Descriptive statistics for indicators of estuarine condition and landscape variables in relation to spatial-setting (i.e., riverine, lagoonal, oceanic) are presented in Table 2a, b. Patterns of variation among landscape setting variables were as anticipated. Across regions, oceanic stations had the highest levels of DO, BI, salinity, distance-to-river, and distance-to-shore. Oceanic stations also had the lowest levels of sediment metals and organics. Riverine stations had the highest sediment pollutants, lowest salinities, DO, BI, and distances to shoreline and river. Lagoonal stations followed riverine sites with lower values but with the same pattern. Suspended solids were highest in lagoonal stations followed by riverine stations and with lowest values for oceanic ones.

We used stepwise regression to determine if spatial-setting variables, rainfall, and proximity to shore and river were important in explaining variation in measures of estuarine condition (Table 3). For the pooled data, the highest variation explained by the models was found for DO (44%) and salinity (58%), with DO decreasing in river locations and salinity decreasing with rainfall and river locations. The explanatory power for the other indicator variables was low, albeit statistically significant, and ranged from 6% to 27%. In the within region analysis, spatial-setting and rainfall explained significant variation in DO and salinity, but remaining R^2 values tended to be low.

Effect of land use/cover

The relationship between land use/cover and estuarine condition was determined with Pearson correlations are shown in Table 4. We found significant correlations between URBAN and most measures of estuarine condition in the pooled data. The amount of agricultural was not associated with measures of estuarine condition in any pairwise comparisons except Arsenic in Cape Cod. Urban land use/cover was consistently correlated with metals concentrations in Cape Cod, but not the other regions.

The correlations observed in the pooled data are the result of capturing a wider range of variation in measures of estuarine condition among sites, and capturing a wider range of variation among riverine, oceanic, and lagoonal sites. This is evidenced in scatter plots of the strongest associations found in the pooled and regional data (Fig. 4).

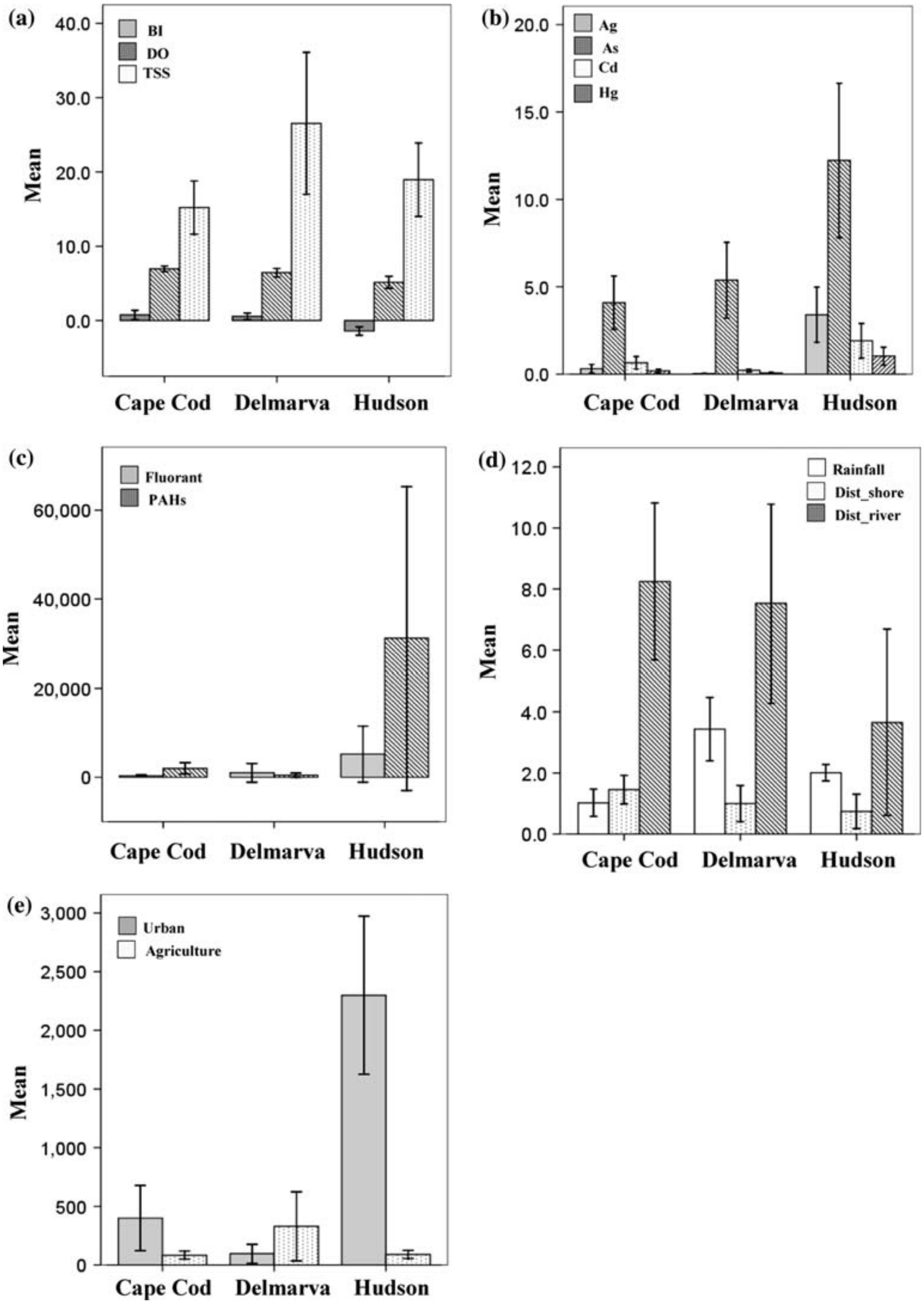

Fig. 2 Means with error bars of 95% CI for estuarine indicators and urban and agriculture land use for Cape Cod, Hudson/Raritan, and Delmarva regions. Units for each estuarine indicator are Table 1. For the others is as follows: Rainfall (cm), Dist_shore and Dist_river (km), Urban and Agriculture (ha)

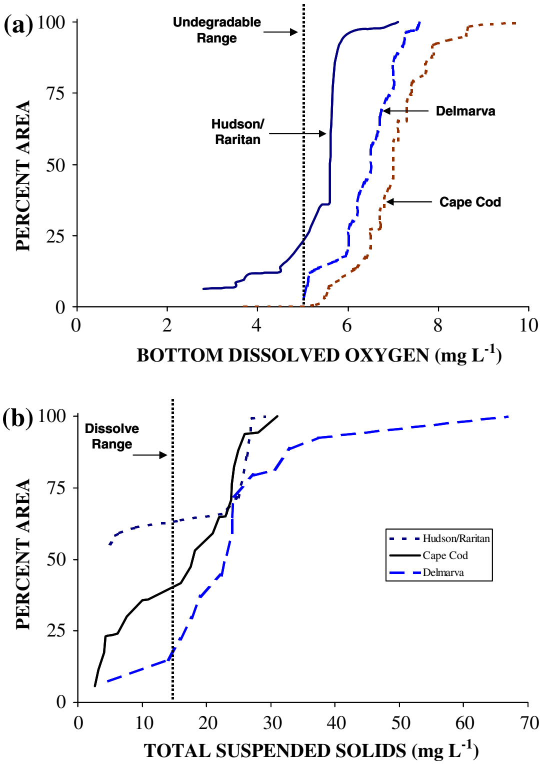

Fig. 3 Cumulative distribution functions (CDFs) for bottom-dissolved oxygen (**a**) for Cape Cod ($n = 25$), Delmarva Peninsula ($n = 11$), and Hudson/Raritan ($n = 15$). The vertical dotted line marks the 5 mg l^{-1} threshold (Paul et al. 1998) where oxygen levels are enough for continuation of life processes. Levels of oxygen below this threshold will result in anoxic environments that could be fatal for fish. CDFs for total suspended solids are shown in **b**. The vertical dotted line marks the 15 mg l^{-1} threshold (Dennison et al. 1993) up to where suspended solids will not interfere negatively with biological processes (i.e., light transmission). Amount of suspended solids larger than this threshold could be deleterious for coastal organisms. Data was sampled in the summer in all three regions

Discussion

Patterns of pollution from the sediment metals and organics that were measured by EMAP reflect regional gradients of land use found in close proximity to estuarine waters in our study areas. Similar relationships have been found in other EMAP research (Weisberg et al. 1992; Paul et al. 1999; NCCR 2001; Paul et al. 2002). With all regions pooled there was a consistent relationship between estuarine condition and urban development. There was no relationship between the amount of agriculture and estuarine conditions when regions were pooled.

Our results showed that dense urban development associated with low dissolved oxygen found in Hudson/Raritan and sediment contamination in the Cape Cod estuarine systems. Hypoxia levels found at the Hudson/Raritan region may reflect the history of high loads of organic wastes going into the Hudson/Raritan estuary complex (O’Shea and Brosnan 2000). Low levels of DO in bottom waters are the common result of increases in nutrient inputs to estuarine systems (Vollenweider et al. 1992; Cloern 2001). Cape Cod and Delmarva show a lower level of coastal urbanization, in addition to their coasts being subjected to stronger ocean currents. DO levels were generally well above 5 mg l^{-1} during the 1990–1993 sampling period in these two regions.

High levels of silver, arsenic, and polycyclic aromatic hydrocarbons in the Hudson/Raritan region were another indication of influence of industrial land use in coastal habitats (Menzie et al. 2002). Paul et al. (2002) also found that variation in sediment contamination levels (metals and PAHs) across small estuarine systems in the mid-Atlantic and southern New England regions were related to the surrounding non-forested wetlands, urban land, and point source effluent volume. Benthic Index, total suspended solids, and the organic pollutants show weak or no relationships to urban or agricultural land use or the spatial-setting variables.

Spatial-setting was an important factor to consider. Oceanic sampling stations had the lowest levels of organic and metal pollutants as would be expected because of their distance from the source of pollutants and flushing by offshore currents. Riverine and lagoonal sites had higher levels of pollutants, lower salinity, lower DO, and higher TSS, a pattern found in other studies (Valiela 1984; Day et al. 1989; Mann and Lazier 1996; Dyer 1997).

The results of land–water relationships found in this study also reflect the experimental problems inherited in the study of large coastal ecosystems. The problem of scale poses a challenge in the study of relationships between estuaries and coastal land use/cover (Kemp et al.

Table 3 Standardized beta coefficients for stepwise multiple regression analysis of spatial-setting variables, rainfall, and proximity to closest river and shoreline regressed against indicators of estuarine condition for the pooled data and the individual regions of Cape Cod, Hudson/Raritan, and Delmarva. In the Delmarva study region the only significant model was for salinity. An analysis of variance was used to test for significance of Regression in multiple regression models. Degrees of freedom for the Regression = k (number of regressor variables in the model), for the Residual = $(n - k - 1)$. Sample size (n) = 51 for pooled, 25 for Cape Cod, 15 for Hudson/Raritan, and 11 for Delmarva. All values of the test statistic, F, shown in the table were significant at 0.01 level. P-values ≥ 0.05 were considered non-significant (n.s.)

Indicator	Dist_shore	Dist_river	Rainfall	Spatial-setting variables			Adj. R^2	F
				Riverine	Lagoonal	Oceanic		
Pooled								
BI					0.377	0.759	0.271	10.49
DO				–0.671			0.439	40.87
TSS			0.497				0.232	16.40
Ag				0.487			0.222	15.57
As				0.384			0.130	8.64
Cd		–0.341					0.098	6.56
Hg				0.290			0.066	4.60
Fluorant				0.433			0.171	11.51
PAHs				0.447			0.184	12.48
Salinity			–0.269	–0.717			0.576	35.65
Temperature						–0.297	0.070	4.85
Cape Cod								
BI		0.431					0.150	5.24
DO								n.s
TSS			0.405				0.128	4.53
Ag								n.s
As						–0.461	0.178	6.20
Cd		–0.430					0.150	5.22
Hg								n.s
Fluorant								n.s
PAHs	–0.445						0.163	5.68
Salinity	0.463						0.180	6.27
Temperature								n.s
Hudson/Raritan								
BI			0.531				0.226	5.10
DO				–0.686			0.429	11.53
TSS			0.523				0.218	4.89
Ag								n.s
As								n.s
Cd								n.s
Hg		0.521					0.216	4.85
Fluorant								n.s
PAHs								n.s
Salinity				–0.618			0.334	8.03
Temperature				0.650			0.378	9.51
Delmarva								
Salinity					0.712		0.457	10.27

2001). Driving-forces in terrestrial habitats are relatively independent of the frequency of delivery, whereas in marine environments an inverse relationship exists between variance and frequency of physical factors affecting ocean biota (Steele 1985). Furthermore, estuaries are largely open ecosystems and experience fluxes from both the land and the sea (Day et al. 1989). In addition, the temporal and spatial scales that characterize ecological processes are quite different in marine and terrestrial systems (Scheffer et al. 1993; Cohen 1994; Steele and Henderson 1994). The results presented here clearly demonstrate the opportunities, and

Table 4 Pearson Product Moment correlations (*r*) reflecting the degree of linear relationship between land use/cover variables (urbanization and agricultural) and indicators of estuarine condition for the pooled and regional data

		BI	DO	TSS	Ag	As	Cd	Hg	Fluoran	PAHs	Salinity
Pooled (n = 51)											
URBAN	*r*	**–0.627****	**–0.612****	0.021	**0.722****	**0.404****	**0.629****	**0.481****	**0.330***	**0.397****	– **0.657****
	p	0.000	0.000	0.885	0.000	0.003	0.000	0.000	0.017	0.004	0.000
AGRICULTURE	*r*	0.072	0.094	0.053	–0.141	–0.014	–0.130	–0.153	–0.071	–0.057	–0.108
	p	0.614	0.506	0.711	0.318	0.923	0.359	0.278	0.617	0.689	0.447
Cape Cod (n = 25)											
URBAN	*r*	–0.306	–0.072	–0.079	**0.594****	0.280	**0.654****	**0.467***	0.265	0.332	**–0.682****
	p	0.137	0.731	0.708	0.002	0.176	0.000	0.019	0.201	0.105	0.000
AGRICULTURE	*r*	–0.121	0.031	0.139	–0.187	**0.572****	0.041	0.053	–0.026	0.130	–0.265
	p	0.563	0.885	0.509	0.370	0.003	0.845	0.802	0.903	0.535	0.201
Hudson (n = 15)											
URBAN	*r*	–0.461	**–0.646****	0.336	0.425	–0.163	0.334	–0.094	0.178	0.198	–0.297
	p	0.084	0.009	0.221	0.115	0.561	0.223	0.738	0.526	0.480	0.282
AGRICULTURE	*r*	–0.133	0.376	0.164	–0.188	–0.041	–0.218	–0.463	0.027	0.005	0.177
	p	0.636	0.167	0.560	0.502	0.885	0.435	0.082	0.923	0.985	0.529
Delmarva (n = 11)											
URBAN	*r*	–0.325	0.288	0.017	0.334	0.110	0.301	–0.140	–0.223	0.365	0.090
	p	0.302	0.364	0.958	0.289	0.733	0.341	0.664	0.485	0.244	0.781
AGRICULTURE	*r*	0.178	0.175	–0.246	–0.290	–0.096	0.189	0.000	–0.226	–0.025	–0.373
	p	0.579	0.587	0.440	0.360	0.766	0.557	0.999	0.479	0.938	0.232

** Pearson correlation is significant at the 0.01 level, and * significant at the 0.05 level; *r* = Pearson correlation; *p* = *P*-value

challenges, of integrating large dataset encompassing broad areas over varying time extents. Spatial-setting of estuarine sampling stations, as well as physical factors, such as rainfall and hydrologic flow patterns, contribute to the noise embedded in the relationships between estuarine ecosystem condition and human activities on land. These sources of variation must be accounted for when working with these important, and potentially valuable datasets.

Model limitations

Poor linear associations between land use/cover and estuarine condition found in our results may be the outcome of unaccounted covariates and other confounding factors that usually diminish the possibility of obtaining statistically meaningful results, as well as from intrinsic limitations in the explanatory variables and the data used. Some of these factors include: (a) a difference in the spatial distribution of EMAP's measuring stations in the three study regions (Kiddon et al. 2003); (b) the total_agriculture_area metric is probably not sensitive enough to capture non-point source pollution from agricultural areas that extend well beyond the proximity model used in this study. Classic descriptive landscape metrics such as size, shape, and proximity to other landscapes may be too simplistic and too static to represent complex and dynamically changing coastal ecosystems (Sklar and Costanza 1991); and (c) the window of observation of estuarine processes used in EMAP is probably not in phase with the type of spatial patterns detected by the statistical model used in this study. The effect of observational scale has been described for terrestrial (Krummel et al. 1987; Turner 1989) and aquatic ecosystems (Hall et al. 1994; Legendre et al. 1997). Future investigations of land use/cover and estuarine condition might benefit from the incorporation of spatial distribution of land-type categories into regression models (Fedorko et al. 2005). Furthermore, our results show the need to improve our ecological data infrastructure (i.e., type, quantity, and quality) since future modeling will be quite restricted by not having overwhelming statistical signals.

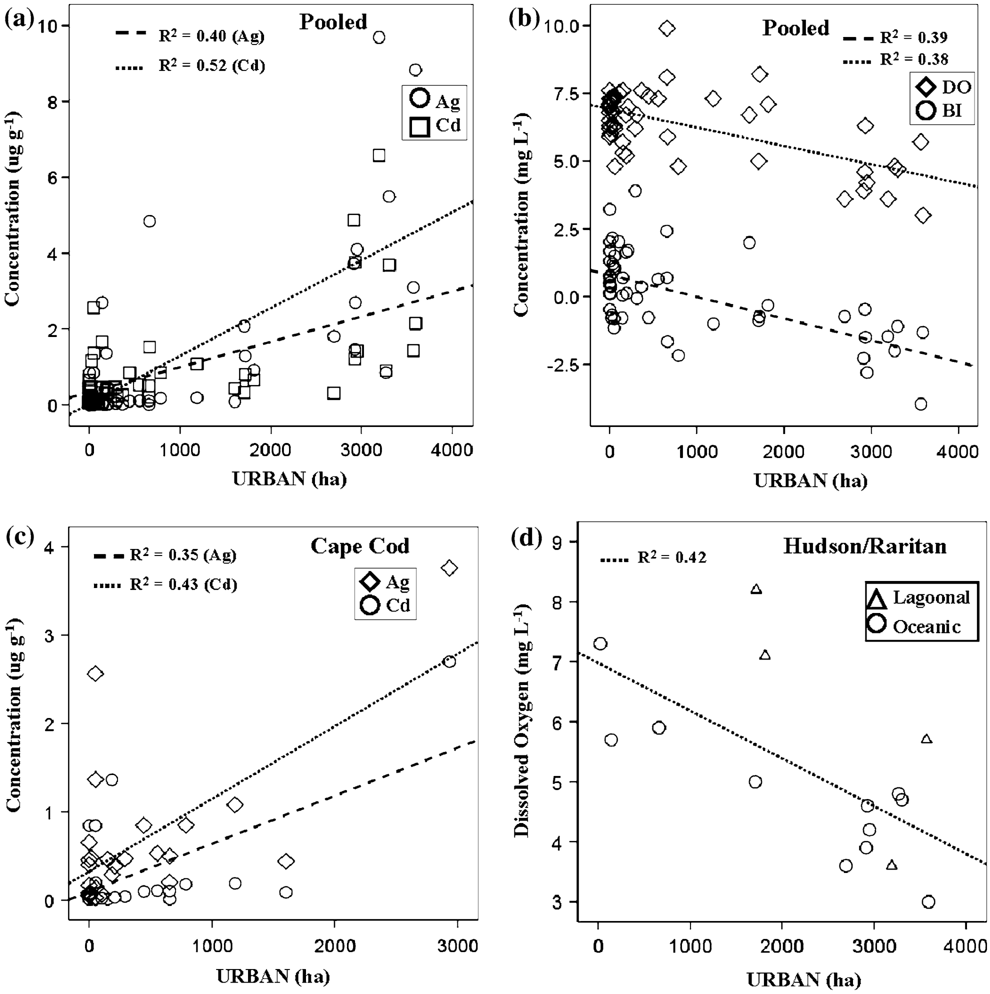

Fig. 4 Trends of urbanization effect on some estuarine indicators for the pooled data (**a**, **b**) and for Cape Cod (**c**) and Hudson/Raritan (**d**) regions. Other significant linear relationships can be seen in Table 4

Recommendations

Our examination of the associations between the pattern of land use and measures of estuarine condition over an extensive region like the Virginian Biogeographic Province suggest a number of future research questions and directions that should be considered. These include:

- Development of connectivity or permeability landscape metrics at different scales and extents may be more appropriate to measure landscape structure than total land use area (Fedorko et al. 2005).
- Development of spatially explicit hydrologic models in conjunction with landscape metrics to account for a more realistic quantification of runoff and nutrients reaching coastal waters.
- Spatial patterns are detected based on the size of the observation window and on the spatial and temporal extent over which observations are made (Wiens 1989). There is a need to link terrestrial and estuarine processes to enhance the development of robust and practical predictive models able to capture the dynamics of land–water relationships in the coastal zone. Modeling development will be

possible only if relationships in the data can be seen and measured.

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