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A National Assessment of Stressors to Estuarine Fish Habitats in the Contiguous USA

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Abstract Estuaries provide vital habitat to a wide variety of fish species, so understanding how human activities impact estuarine habitats has important implications for management and conservation of fish stocks. We used nationwide datasets on anthropogenic disturbance to perform a quantitative assessment of habitat stressors in US estuaries. Habitat stressors were characterized by four categories of indicator datasets: (1) land cover/land use, (2) alteration of river flows, (3) pollution sources, and (4) eutrophication. These datasets were combined using a multiscale hierarchical spatial framework to provide a composite stressor index for 196 estuaries throughout the contiguous USA. Investigation of indicator patterns among 13 defined USA coastal subregions revealed clear differences across the USA attributable to both natural variation as well as differences in anthropogenic activities. We compared the mean composite scores for each subregion and found the lowest stressor index scores in the Downeast Maine and the Oregon Coast subregions. Subregions with the highest stressor index scores were the Southern California Bight (due to land cover changes, river flow alteration, and pollution) and Mid-Atlantic Bight (due to land cover changes, pollution, and eutrophication). Inland-based measures of pollutants, river flow, and land use all showed strong correlations with eutrophication measured within estuaries. Our approach provides an indicator-based assessment for a larger number of estuaries than has been possible in previous assessments, and in the case of river flow, for variables which previously have not been evaluated at a broad spatial scale. The results of this assessment can be applied to help prioritize watershed and estuarine restoration and protection across the contiguous USA.

Keywords Estuary · Habitat assessment · River flow · Pollution · Eutrophication · Land cover

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Introduction

Estuaries are critically important biological, cultural, and economic habitats. Because a variety of fish and shellfish utilize estuaries as vital nursery habitats, estuaries support a multitude of recreational and commercial fishery species (Boesch and Turner 1984; Day et al. 1989; Bell 1997; Nelson and Monaco 2000; Beck et al. 2003; MacKenzie and Dionne 2008; Barbier et al. 2011). The close proximity of dense human populations and resulting anthropogenic pressures has led to a wide array of threats in many estuary environments (Kennish 2002). As a consequence, estuarine habitat has been altered or lost at alarming rates throughout the USA, and the ability of these habitats to provide important ecosystem services has likewise been impacted.

Of the threats facing estuaries, the most severe include habitat conversion and loss, altered freshwater flows, accumulation of chemical contaminants, and eutrophication. Anthropogenic activities such as coastal development and urbanization, conversion for agriculture, channelization, dredging, coastal armoring, and fossil fuel development can directly alter or destroy estuary and coastal habitats (Stedman and Dahl 2008; RAE 2009). Alteration of hydrology in estuaries resulting from changes to freshwater flow and tidal action can impact water quality, reduce connectivity, and lead to marsh subsidence (MBNEP 2002a, b), ultimately affecting estuarine habitat function. Pollution draining to estuaries poses "unacceptable risks" not only to sensitive estuarine habitats and the fish and other species that depend on those habitats, but also to humans who live, work, or play near contaminated estuarine habitats (USEPA 2008a, b). Similarly, excess nutrient inputs from land-based sources (e.g., leaking septic systems, untreated sewage effluent, and agricultural runoff) can lead to eutrophication, which threatens habitat function through water quality declines, dense algal blooms (including harmful algal blooms), hypoxia, and salt marsh loss (Kennish et al. 2007; Deegan et al. 2012).

Understanding the role of estuary habitats in supporting recreational and commercial fish stocks is essential information for resource managers. Likewise, improved understanding of the impacts to estuary habitats can help target the right types of restoration where they are needed most. In this paper, we examine the consequences of major human impacts to the estuary and catchments delivering materials to estuaries through development of a comprehensive national assessment of the nation's estuarine fish habitats.

Previous assessments of estuarine condition (Bricker et al. 2007; USEPA 2005, 2007; Heinz Center 2008; Kimbrough et al. 2008) have provided the foundation for this research. Although these studies yielded important insight into the condition and functioning of our nation's estuarine habitats, they were limited in geographic scope or in the range of threats to habitat quality that were evaluated. The current assessment builds from these previous assessments, using a synthesis of available data to develop indicators of stressors to estuarine fish habitats based on four key estuary threats: land use in estuarine watersheds and shorelines, alterations to freshwater flow, chemical contaminants, and eutrophication. Many other factors may contribute to the condition and functioning of estuarine habitats, but lack data at a nationally consistent scale needed for an analysis of this scope. Using the four indicators listed above, we are able to answer questions about the overall condition of our nation's estuaries, as well as make comparisons across the contiguous USA to identify relatively undisturbed areas and regions exhibiting the greatest disturbance. We further investigated information on anthropogenic threats to examine linkages between freshwater and estuary systems.

Methods

The national estuarine assessment combined landscape and in situ estimates of habitat stressors to produce a single composite stressor index for each estuary. The assessment is built upon the assumption that in addition to local factors, the nature and intensity of activities within the watershed influences estuarine habitats. It required two essential features: (1) existing environmental monitoring data for important indicators of habitat disturbance at the national scale and (2) a spatial framework to organize indicator data. We combined these two features to produce a spatially referenced multicomponent index that captured four categories of potential disturbances to estuarine habitats: land cover, river flow, pollution, and eutrophication.

Study Area and Spatial Framework

The assessment investigated major stressors in 220 estuaries and their associated upland watersheds across the contiguous USA. We developed a nested spatial hierarchy to integrate landscape components along the summit-to-sea continuum for use investigating the impacts of anthropogenic activities to estuaries. We delineated polygons in a geographic information system (GIS) using the National Oceanic and Atmospheric Administration (NOAA) Coastal Assessment Framework (CAF) (NOAA 2007) as a starting point, adapting and adding spatial units to meet our assessment needs.

We defined two primary units of interest within the coastal assessment spatial framework: estuaries and their watersheds. Estuary polygons (220 total) ranged from relatively small river mouth estuaries to large deltas and embayments, and from shallow systems to deep inland seas (e.g., Puget Sound). Estuaries were delineated as distinct units, except in cases of large estuarine systems with many tidal tributaries such as the Chesapeake. The larger estuary systems (e.g., Chesapeake Bay, Puget Sound) were divided based on natural bathymetric breaks. We defined watersheds (346 total) within the framework as units that flow into estuaries. Watershed units were modified as necessary from the CAF, which was originally based on US Geological Survey (USGS) Hydrologic Unit Classification 8-digit watersheds (HUC-8; USGS 2008).

The coastal spatial framework was nested hierarchically to facilitate analysis at multiple scales. Base layer polygons were assigned membership to 1 of 6 regions, 13 subregions, and 22 bioregions to allow for regional comparisons based on jurisdictional and biogeographic boundaries. Bioregions were formed based on natural geography using major regional breaks consistent with generally accepted biogeographic classifications (Briggs 1974; Cook and Auster 2007; NOAA 2004; Spalding et al. 2007; Wilkinson et al. 2009). Bioregions were combined into 13 larger subregions for the purposes of statistical analysis to ensure adequate sample size. The coastal assessment spatial framework also includes administrative boundaries and jurisdictional considerations (e.g., state boundaries, etc.) based on legally vetted boundary layers in the Multipurpose Marine Cadastre (MMS 2008). Including a variety of regional classification options improves the utility of our assessment results for resource managers by allowing a range of regional comparisons.

Index Development

The assessment consisted of four component indices of habitat stress: land cover, river flow, pollution, and eutrophication. Each component index itself is a compilation of multiple variables describing potential anthropogenic disturbance to estuarine habitat (Fig. 1; Appendix 1). Component indices were developed using national datasets as described below. We chose datasets that (1) represented indicators of anthropogenic activities likely to influence fish habitat, based on evidence found in habitat ecology literature, and (2) had sufficient resolution for meaningful analysis within the coastal spatial framework and geographic breadth across the framework. For all indices, a percentile rank score of 1 represented estuaries with the greatest stress; scores were inverted where necessary to maintain this consistency in interpretation between index scores. Component indices were combined into a composite stressor index that describes the estimated cumulative stress on the habitats of USA estuaries.

Land Cover The land cover component index analyzed data from the NOAA Coastal Change Analysis Program (C-CAP) (NOAA 2011) to characterize the land cover of US estuary shorelines and watersheds. Data from 2006 represent the best available information on current land cover, while land cover change was calculated over the 10-year interval between 1996 and 2006. C-CAP data were available to calculate the land cover component index for every estuary defined in our coastal spatial framework.

The C-CAP database contains a total of 25 land cover classes. Several of these C-CAP classes (unconsolidated shore, bare land, tundra, snow/ice, water, and unclassified) were not deemed important to the analysis of habitat stress and omitted from further consideration. We combined the remaining 19 C-CAP classes into five key land cover classes expected to impact estuaries. Data were summarized to investigate land cover in two key zones: estuarine shorelines and estuarine watersheds. Estuarine shoreline zones were designated by selecting all areas within 30 m of grid cells identified as water in the 2006 C-CAP dataset and within 500 m of estuary shorelines defined by the coastal assessment spatial framework. Estuarine watersheds are the spatial units draining into each individual estuary. To compensate for minor spatial discontinuities between the coastal framework and C-CAP datasets, all land cover cells seaward of watersheds were attributed to the nearest watershed. The area of grid cells within each estuarine shoreline and watershed was tabulated for each of the five land cover classes and expressed as a proportion of the area.

The impact of land cover stressors on estuaries was calculated as the percent area of each of the five land cover classes for both estuarine shorelines and watersheds, resulting in a total of ten land cover variables (Appendix 1). Agriculture and developed land cover were assumed to have a presettlement baseline area of zero; therefore, land cover for these variables was calculated from 2006 C-CAP data. The other three land classes (estuarine wetland, palustrine wetland, and undeveloped) did not have a national baseline available for presettlement conditions, so the difference in coverage between 2006 and 1996 was calculated as a metric of land cover change for these classes. All land cover variables were calculated as percent area except developed land cover intensity, which was a density-weighted score calculated using the density factors listed in Appendix 1. The development variables, therefore, do not represent a true area value, but instead allow for development intensity to be weighted proportionally to its hypothesized impacts (Hale et al. 2004; Bilkovic and Roggero 2008). To maintain consistency in the interpretation of variable scores (where higher scores represent higher impacts), percent area values for estuarine wetland, palustrine wetland, and undeveloped were subtracted from 100 %. To develop the final land cover component index, we calculated the average of the ten variables and represented the result as a percentile, with 1 representing the highest land cover stress (Fig. 1).

River Flow The river flow component index integrated several indicators of river flow and material recruitment to estimate the potential of altered flow regimes to affect estuarine habitats. A total of ten variables contributed to the overall river flow component index. The first variable was the density of upstream dams, serving as an indication of the degree to which water, sediment, detritus, and other structural materials are stored above estuaries. We used The Nature Conservancy's Indicators of Hydrologic Alteration (IHA) software (Richter et al. 1996; ConserveOnline 1996) to derive nine additional variables summarizing river flow which could be directly related to habitat disturbance. These flow variables provided information on the recent status of average, high, and low flows, and their trends over time.

We estimated the density of upriver dams using the Army Corps of Engineers' National Inventory of Dams (NID; USACE 2010). Because inaccuracies of geospatial dam locations in the NID are known to exist, the latitude and longitude of all dams catalogued in the NID were cross-checked visually using Google Earth (D. Infante, Michigan State University, unpublished data). Upriver dam density was calculated by dividing the number of dams by the watershed drainage area upstream of each estuary unit, estimated from the National Hydrography Dataset Plus (NHD+; HSC 2011).

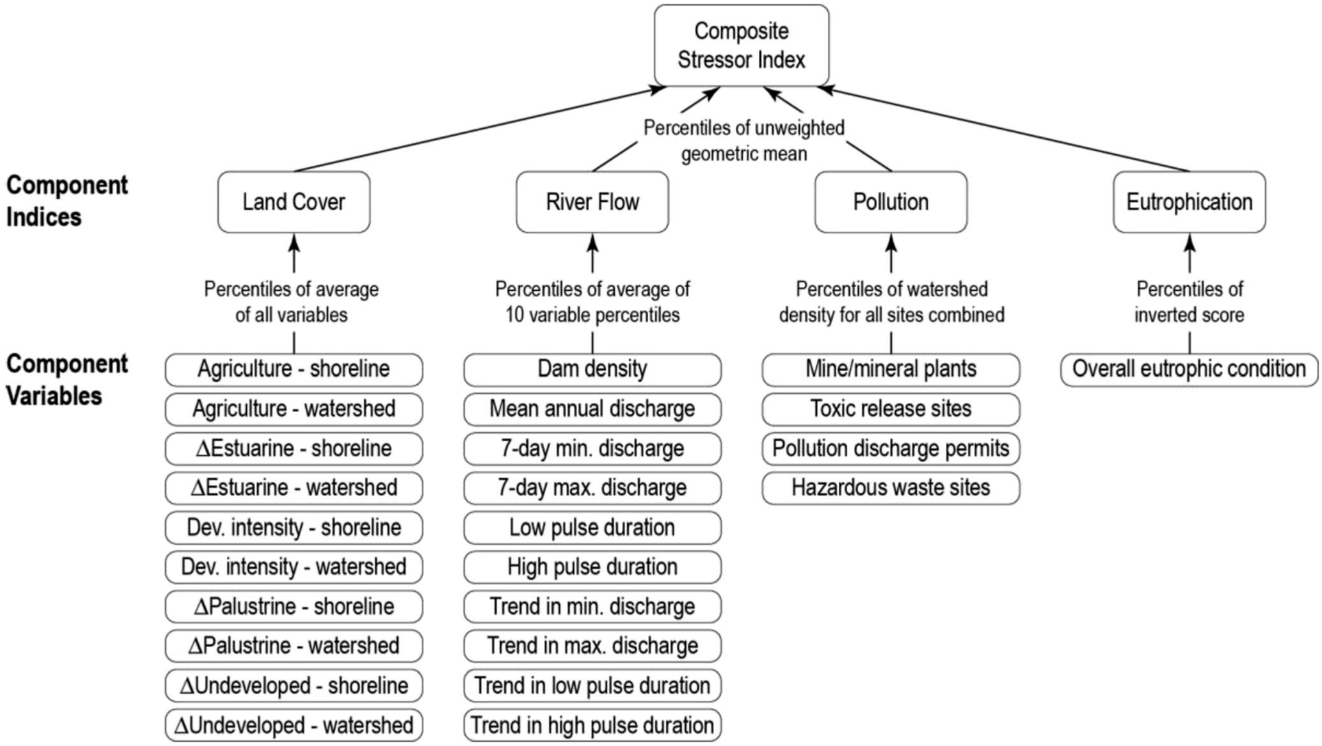


Fig. 1 Overview of the estuary assessment process including individual variables included in the component indices and a summary of each step taken to produce the composite stressor index

We developed river flow variables using flow data available for US rivers from USGS surface water gages (USGS 2010). Exceptions included data for the Tijuana River, obtained from the International Boundary and Water Commission's monitoring station at the USA–Mexican border (IBWC 2010), and data from two gages on Canadian rivers obtained from Canada's surface water survey (EC 2010). Because the focus of this study was on estuarine habitats, we selected the lowest-elevation flow gages available in an estuary's watershed for use. Additionally, data collection focused on gages with at least 35 years of data in order to get the broadest possible estimate of trends. The total number of years of available data varied by individual gage. Due to these data constraints, the number of units in our study area that had available flow data to calculate the river flow component index was restricted to 155 estuaries (70 %).

We used daily flow estimates obtained from flow gages as inputs for IHA software (Richter et al. 1996; ConserveOnline 1996). River flow characteristics were assessed using five ecologically-relevant outputs from IHA: mean annual discharge (MAD), 7-day minimum discharge, 7-day maximum discharge, low pulse duration, and high pulse duration (Fig. 1; Appendix 1). We calculated the average annual value of each of these five outputs over the most recently available 15-year period of data. To facilitate comparisons across watersheds of variable size and discharge, MAD was divided by the watershed drainage area (as estimated from NHD+), and minimum and maximum discharge were divided by MAD. An additional four flow variables were developed by examining the linear coefficient of the trend in annual values (over the entire annual time series available) of 7-day minimum discharge, 7-day maximum discharge, low pulse duration, and high pulse duration. These, in addition to dam density, provided a total of ten river flow variables.

We derived the river flow component index by first calculating percentiles for each of the ten river flow variables to generate scores that varied from 0 to 1.0. These were averaged, and the percentiles of this average were used as the river flow component index (Fig. 1).

Pollution We used a landscape approach to develop the pollution component index, investigating publicly available national datasets on mines, toxic releases, pollution discharges, and hazardous waste sites within watersheds discharging into estuary units (Fig. 1; Appendix 1).

Pollution sites were summarized by Esselman et al. (2011) using the NHD+ database. Each stream segment in the NHD+ was assigned a value representing the total summed number of mine, toxic release, pollution discharge, and hazardous waste sites in that segment's watershed. The accumulate tool, available with NHD+, was used to accumulate all pollution sites in the watersheds, based on a nationwide watershed habitat assessment (P. Esselman, personal communication, Michigan State University).

To estimate the number of pollution sites affecting each individual estuary within the National Fish Habitat Partnership

(NFHP) coastal framework, we selected NHD+ reaches described as "Stream/River" that connected to features described as "Coast". Instances of split channels, which duplicated accumulated data, were removed manually. The total number of pollution sites was summed by estuary for all terminal segments within 500 m of an estuary unit. This value represents the total number of pollution sites, including Toxic Release Inventory, National Pollution Discharge Elimination System, Superfund, and mine sites in an estuary's NHD+ watershed(s). We scaled these data by total watershed area (km^2) flowing into an estuary. Resulting pollutant densities for all estuaries were assigned a percentile score, where 1 represented an estuary with the highest density of pollution sources and 0 was the lowest density.

Eutrophication The eutrophication component index consisted of a single input variable—the Overall Eutrophic Condition (OEC) index—to represent potential degradation of habitat resulting from eutrophication (Fig. 1; Appendix 1). The OEC index was estimated for the National Estuarine Eutrophication Assessment (NEEA; Bricker et al. 1999; 2007) using both quantitative and categorical information on the symptoms of eutrophication. The updated NEEA in 2007 included 141 estuaries; we used data from this analysis where available. In cases where values from the 2007 assessment were missing for a given estuary unit within the coastal assessment framework but available from the 1999 assessment, the 1999 assessment values were substituted. These substitutions increased the number of estuaries with eutrophication information to 149 (68 %). Eutrophication data were particularly limited on the Pacific Coast, where only 47 % of estuaries had eutrophication data available.

The OEC is described in detail in Bricker et al. (1999, 2007). Since the expression of eutrophic conditions cannot be predicted by nutrient inputs alone, the OEC assesses the severity, spatial extent, and frequency of high chlorophyll a concentrations, macroalgal blooms, impacts to dissolved oxygen, nuisance algal blooms, and impacts to submerged aquatic vegetation. The final OEC index assigns a value between 0 and 1 to each estuary, with 1 indicating a highly eutrophic condition.

To calculate the component index of eutrophication for our assessment, we calculated percentiles of the raw OEC scores available from the 2007 (and 1999, where necessary) NEEA report (Bricker et al. 1999, 2007).

Composite Index of Habitat Stressors We calculated the composite stressor index for each estuary by combining the four component index scores (land cover, river flow, pollution, and eutrophication). While correlation between landscape variables is inevitable, each variable provided unique information to the composite index. We tested correlation between component indices with Spearman's rank correlation coefficient, and satisfied the criteria of Posa and Sodhi (2006) that all cross-correlations were not large ($p<0.5$). Due to data limitations, not all estuaries had a score available for all four component indices. We assigned a composite index score only when an estuary had at least three of the four component index scores available.

To calculate the composite stressor index, we used a geometric mean of the inverted value of the component indices. The geometric mean placed greater emphasis on components with high stress (lower inverted values) for each estuary. The resulting geometric mean was then rescaled from 0 to 1 as a percentile and reinverted to be consistent with the direction of the component scores. This produced a composite index that integrated the combined risk of habitat disturbance from the four classes of anthropogenic influence, while weighting highly stressed scores more heavily. For the display map, final scores were divided into equal quintiles: 0–20 (very low stress), 20–40 (low stress), 40–60 (medium stress), 60–80 (high stress), and 80–100 (very high stress).

Comparative Analyses

Regional Comparisons We conducted a series of statistical analyses to compare stressors among the 13 subregions. Unequal sample sizes existed between subregions due to variability in the number of estuaries within each bioregion and differences in data availability. To confirm the equality of variances in the data between subregions, we first used a Levene's test for each of the four component indices and the composite index. We next performed a one-way ANOVA to compare mean scores among subregions for each of the four component scores and the composite stressor index. Statistical significance for all tests was determined with $\alpha=0.05$. A Tukey's range test was used post hoc to compare individual group means. Additionally, index scores were summarized as area-weighted means (based on the total estuary area) for each subregion. Comparisons among the area-weighted subregional means were not statistically analyzed.

Predictors of eutrophication We examined how watershed metrics (land cover, river flow, and pollution) predicted metrics measured directly within estuaries (eutrophication). First, we examined individual component variables in addition to component index scores to determine whether specific metrics in our dataset were strong predictors of eutrophication. Next, we examined individual component variables to determine whether specific metrics within component scores had greater predictive power than the overall component indices. For land cover and river flow variables, we screened each component variable set and included variables with the highest correlations ($p<0.1$) for additional analysis. In both sets of analyses, we evaluated the relative explanatory power of predictors using forward and backward stepwise regression and used consensus predictor diagnostics (standard error, standardized β, and p value) as the basis for inclusion of component variables. We performed these models for both the entire dataset, as well as for estuaries broken out by coast (Pacific, Gulf of Mexico, and Atlantic).

Validation We expected component and composite indices of habitat stress to have internal consistency and offer partial redundancy. Each component is expected to add information to the composite stressor index, but because all four scores could not be measured for all estuaries, individual components should also reinforce the others. We used Spearman's rho to test for correlations among component and composite scores, and multiple regression of component scores on the composite score to determine the relative importance and redundancy of each of the four component indices.

The ranking procedure removes some of the variation associated with component variables. We examined the potential loss in variation by a second calculation following Halpern et al. (2009), in which we normalized all component variables between 0 and 1, with a value of 1 representing highest stress (see Appendix 1). In contrast with the ranking procedure, this normalized score retained the variation associated with the component variable. Component variables were than averaged together to produce a component index, and the four component indices were then averaged to produce a normalized composite index of habitat stress, following the same rules as the ranking index for missing component index values. The two sets of scores were highly correlated (r=0.76, p<0.01) with equal variation across the range component index values, demonstrating that the original composite stressor index was not strongly biased by ranking procedures.

We compared our scores with two additional assessments of at least national scope to provide independent validation of the composite stressor index. First, an assessment of river fish habitats was conducted by Esselman et al. (2011) comparing potential freshwater habitat stressors with fish data across the contiguous USA to develop stressor thresholds at which fish assemblages simplified. We compared our composite scores with their network-scale cumulative disturbance scores, for which higher scores mean less disturbance. Secondly, we compared our results with the Human Footprint Index (HFI; Sanderson et al. 2002), a measure of the relative human influence within terrestrial biomes. The HFI was developed using data on population density, land transformation, accessibility, and electrical power infrastructure, with scores for each data type standardized to reflect estimated impacts on human influence. Comparisons with the HFI were calculated based on average values measured within the catchment of each estuary unit.

Results

Indices Habitat Stress

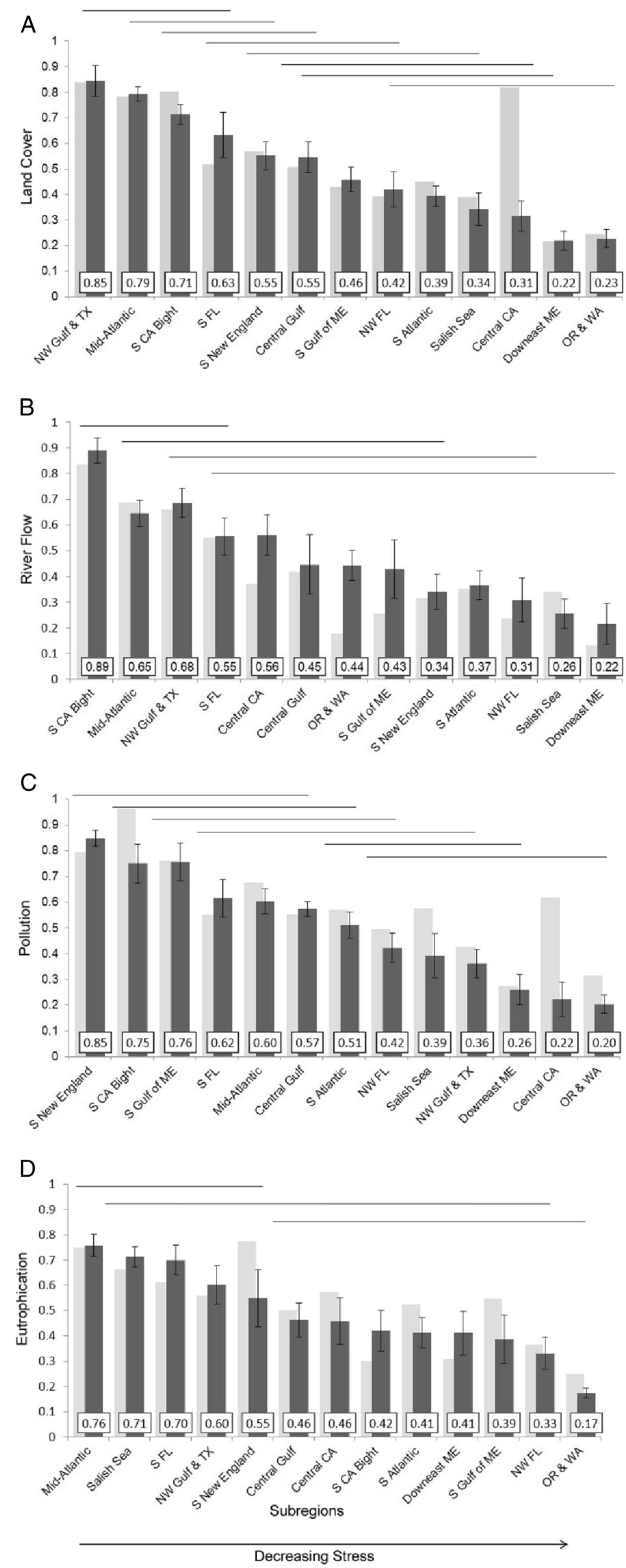
Our methodology generated at least three composite indices of stress for 196 estuaries, allowing us to calculate the composite stress index for 89 % of the estuaries in the coastal framework. We focused our analysis on patterns in the estuaries' component and composite indices at the subregional level. Variable scores as well as component and composite indices for individual estuaries are available online (USGS 2011).

Land Cover The land cover component index differed significantly among subregions ($F_{12,\ 208}$=20.68, p<0.001). Tukey' post hoc comparisons of the subregions revealed that the highest degree of land cover alterations occurred in the Northwestern Gulf and Texas as well the Mid-Atlantic Bight (Fig. 2). Many of the estuaries in the Southern California Bight and Southern Florida have also experienced a high degree of land cover alteration. Estuaries in Downeast Maine and Oregon–Washington had the lowest degree of land cover alterations. When summarized by an area-weighted mean, Central California had a very high land cover component index, driven by the large-scale agricultural and urban alterations in the San Francisco Bay estuarine system (Fig. 2).

Estuaries in certain subregions were heavily impacted by conversion of estuarine shoreline or watershed area for either agriculture or development (Table 1). In general, development was more common on estuary shorelines, while agriculture was more prevalent in estuarine watersheds. For example, shoreline conversion to agriculture never surpassed 3 % in any subregion except Central California (12.14 %). In contrast, estuary shoreline development varied from 3 to 26 % development in all but one subregion (Southern California Bight=67 %). Within estuarine watersheds, agriculture ranged from 2.71 % on the Oregon and Washington coast to over 37 % in the NW Gulf of Mexico and Texas. Development in local catchments ranged from 2.6 % in Oregon and Washington to nearly 28 % in the Southern California Bight. The combined effect of agricultural and urban land conversion within an estuary's local catchment was particularly high in the Northwestern Gulf and Texas (44.9 %), Southern Florida (41.5 %), Mid-Atlantic Bight (40.2 %), Southern New England (32.5 %), and Central Gulf of Mexico (22.5 %).

River Flow The river flow component index differed significantly among subregions ($F_{12,\ 143}$=6.87, p<0.001). Tukey' post hoc comparisons of the subregions showed that the Southern California Bight, Mid-Atlantic Bight, and Northwestern Gulf and Texas had the highest degree of river flow alteration in the nation. Downeast Maine and the Salish Sea had the lowest component scores, significantly lower than the three previously mentioned subregions (Fig. 2).

Fig. 2 Component stressor indices averaged and ranked by subregion for **a** land cover, **b** river flow, **c** pollution, and **d** eutrophication. *Dark gray vertical bars* represent the mean of the individual estuary component index scores within each subregion, while *light gray vertical bars* represent the area-weighted means. *Error bars* represent standard error. *Dark vertical bars* (subregions) that do not fall under the same *horizontal bar* are significantly different than one another (one-way ANOVA, Tukey's post hoc comparison)



When summarized by area-weighted mean, the distribution of scores for the river flow component index was similar to the arithmetic estuary mean. The area-weighted scores for the Oregon and Washington, Central California, and Southern Gulf of Maine subregions were noticeably lower than their mean scores per estuary driven by the relatively low component scores for the larger estuaries of San Francisco Bay, Columbia River, and Cape Cod Bay, respectively.

Pollution The pollution component index of the estuaries also differed significantly between the subregions ($F_{12, 207}$=12.83, p<0.001). Tukey's post hoc comparisons of the subregions revealed that estuaries of Southern New England, with their long histories of industrialization, had the highest mean pollution component index in the nation. Scores for the Southern California Bight, Southern Gulf of Maine, Mid-Atlantic Bight, and Central Gulf of Mexico subregions also indicated heavy disturbance from pollution (Fig. 2). Estuaries in both the Central California and Oregon and Washington subregions had the lowest unweighted mean pollution index. However, when summarized by an area-weighted mean index, Central California had a higher pollution component index (Fig. 2) due to a heavy degree of pollution in the large San Francisco Bay estuary system. A relatively high pollution index in South and Central Puget Sound also drove the area-weighted pollution index up for the Salish Sea subregion (Fig. 2).

Eutrophication The mean eutrophication component index of national estuaries differed significantly between subregions ($F_{12, 137}$=8.52, p<0.001). Overall, the subregions fell into two significantly different groups: low to moderate scores and moderate to very high scores (Fig. 2). On the extreme ends, the Mid-Atlantic Bight, Salish Sea, and Southern Florida subregions had the highest mean eutrophication index, while the Oregon and Washington, Northwest Florida, and Southern Gulf of Maine subregions had the lowest values.

When summarized by an area-weighted mean, many subregions exhibited similar scores to their arithmetic mean. Exceptions were observed in subregions with larger estuarine systems threatened by eutrophication. These included Southern New England (Long Island Sound and Narraganset Bay), Central California (South San Francisco Bay), South Atlantic (St Johns River), and Southern Gulf of Maine (Cape Cod and Massachusetts Bay; Fig. 2).

Composite Stressor Index The composite stressor index differed significantly between estuaries in different subregions ($F_{12, 184}$=29.67, p<0.001). Tukey's post hoc comparisons of the subregions revealed Southern California Bight estuaries to have the highest composite stressor score. The Mid-Atlantic Bight, Northwest Gulf of Mexico and Texas, Southern Florida, and Southern New England subregions (in decreasing order) also have a relatively high mean composite index (Fig. 3). In contrast, estuaries in Oregon and Washington as well as Downeast Maine had a very low composite stressor index. A majority of the estuaries of Northwestern Florida also had low composite stressor scores.

Composite score variation among subregions did not change substantially when summarized by an area-weighted mean (Fig. 3). The most notable difference was for Central California, which had a much higher area-weighted score. While many of the smaller Central California estuaries had

Table 1 Estimated agricultural (Agr) and developed (Dev) land cover conversion for estuarine shorelines and watersheds in the 13 subregions. All data in table are presented as the percent of total land area

Subregion	Estuary shoreline			Estuary watershed		
	% Agr	% Dev	Total	% Agr	% Dev	Total
Downeast Maine	0.88	4.12	5.00	5.38	2.79	8.17
Southern Gulf of Maine	1.05	11.88	12.94	6.65	14.96	21.61
Southern New England[a]	1.29	21.75	23.04	11.07	21.38	32.45
Mid-Atlantic Bight[a]	2.86	11.28	14.15	26.85	13.37	40.22
Southeast Atlantic	0.26	3.36	3.62	15.01	7.03	22.04
Southern Florida	0.01	10.54	10.55	24.71	16.81	41.52
Northwest Florida	0.21	6.65	6.86	11.44	6.34	17.78
Central Gulf of Mexico	0.80	3.98	4.77	16.11	6.37	22.48
NW Gulf of Mexico and Texas	1.02	7.34	8.37	37.68	7.23	44.90
Southern California Bight	0.17	67.94	68.11	3.36	27.64	31.00
Central California	12.14	25.73	37.88	11.46	9.49	20.95
Oregon and Washington	2.28	5.95	8.23	2.71	2.61	5.32
Salish Sea	0.39	7.77	8.17	5.44	11.22	16.66

[a] Due to overlapping subregional delineations, one estuary unit (Hudson-Raritan estuary) was included in analyses for both of these subregions

relatively low composite stressor scores, these were overshadowed by the high score of the large San Francisco Bay estuarine system. This same pattern occurred in the Salish Sea, where a majority of the estuaries were assigned a low composite index. However, central Puget Sound, which makes up 35 % of the estuarine area in the Salish Sea subregion, had a high composite stressor index, thereby increasing the area-weighted score. When summarized by area (pie charts in Fig. 3), nearly all (97–99 %) of the estuarine area of the Southern California and Mid-Atlantic Bights received a score of either high or very high stress. In the least disturbed subregions, Oregon and Washington and Downeast Maine, 98–100 % of the estuaries were scored with either low to very low stress (Fig. 3).

Predictors of Eutrophication

Regression analysis of component indices and component variables indicated that the best predictors of eutrophication differed depending on the scale of analysis. At a national level, both river flow and land cover indices were strongly correlated with eutrophication scores (Table 2). However, multiple regression of the eutrophication score using the three other component scores as predictors ($F_{3,104}$=4.737, p=0.004, R^2=0.12) revealed that the best predictor of the eutrophication score was land cover; the standardized β for land cover (0.329, p=0.002) was over three times the values for river flow (β=0.087, p>0.1) or pollution (β=−0.094, p>0.1). These patterns were paralleled when the component variables with the greatest explanatory power were used. In this analysis, the combined percentage of land converted to agriculture or development had two to three times the explanatory power as determined by β scores as the other three component variables (Table 3). However, separate models of the three coasts revealed that river flow variables had greater explanatory power than land cover metrics. In Atlantic estuaries, high pulse duration explained more variation than two land cover metrics and pollution values. In the Gulf of Mexico, a combination of dam density and mean annual discharge explained the bulk of the variation in the eutrophication score. In the Pacific, the sole significant predictor was dam density (Table 3). Interestingly, the direction of some relationships varied by coast: in estuaries of the Gulf of Mexico, increasing density of dams correlated with lower eutrophication symptoms, while on the Pacific coast, dam density appeared to increase likelihood of eutrophication.

Validation

A majority of the component indices of stress were positively correlated with each other and all were positively correlated with the composite stressor index (Table 2), indicating some redundancy among parameters. The only component indices that did not exhibit strong correlations with each other were river flow and eutrophication indices with pollution. Despite equal weighting of components in the composite index calculation, the land cover index had a much higher correlation with the composite score than the other three components. When we compared the relative influence of components on the composite score using multiple linear regression, the land cover component was again the most important determinant of the composite score as judged by standardized β values (β=0.455, p<0.0005), followed by the eutrophication (β=0.391, p<0.0005) and river flow (β=0.361, p<0.0005) components. The least important predictor of the final score was the pollution component (β=0.254, p<0.0005).

Composite stressor scores were also consistent with broad-scale indicators of anthropogenic disturbance. Scores for the composite stressor index were positively correlated with watershed network-scale cumulative disturbance scores (Esselman et al. 2011) across the USA (r=0.50), and negatively correlated with the human footprint index (r=0.76; Fig. 4). This second correlation exhibited a marked threshold relationship: when the human footprint was less than 20 %, composite scores were of moderate to very low stress. Conversely, when the human footprint was greater than 50 %, composite scores were consistently high or very high stress. In-between these footprint values, the entire range of habitat stress was possible.

Discussion

This analysis presents a national-scale assessment of habitat stress in estuaries, using component indicators that are strongly related to processes that modulate estuarine habitat quantity or quality. Previous assessments of the nation's estuaries have provided limited resolution (single regions or limited number of estuaries) or limited scope of analysis (fewer indicators of habitat stress), and this analysis broadens previous assessments in both ways. We found that across the contiguous USA, some estuaries and subregions have much higher overall habitat stress than others, and not surprisingly, those with highest stress tend to be in places with relatively high anthropogenic influence. Our analysis also illustrates that different regions are subject to different habitat stressors, and suggests that estuaries in different regions may respond differently to the same stressors. Both conclusions are generally consistent with other analyses of national scope including EPA's assessment of National Estuary Program (NEP) estuaries (EPA 2007), and within watersheds influencing estuaries (Esselman et al. 2011). These comparisons indicate that composite scores are broadly valid across the contiguous USA, and can provide an indication of habitat stress for areas not well covered by previous assessments. At a national level, land cover scores were the most important predictors of overall habitat stress, although at finer spatial scales, other

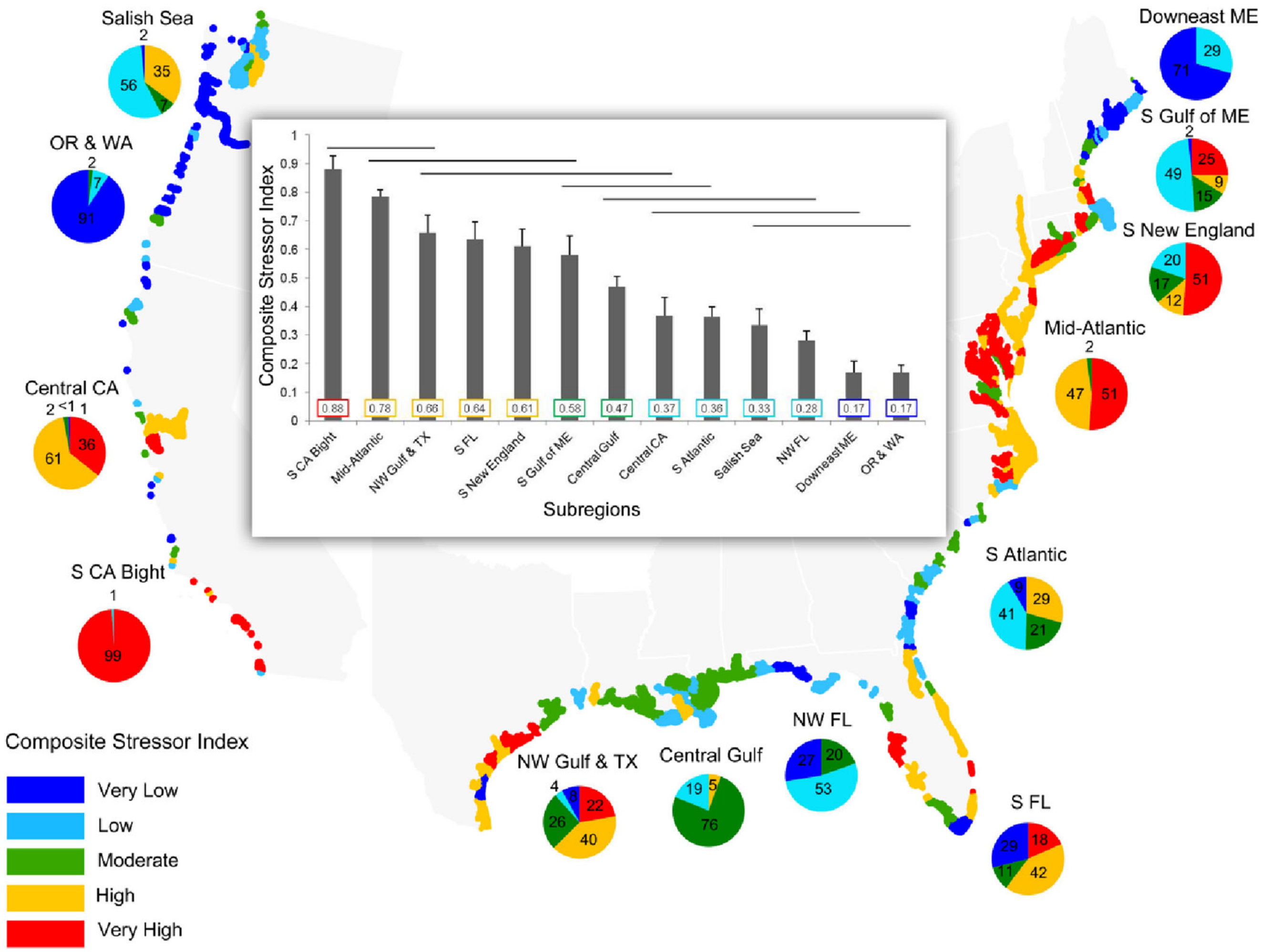


Fig. 3 Scores for the composite stressor index; map shows scores for individual estuaries, while *pie charts* represent the percentage of total estuarine area for each subregion falling within each of five index categories (very low to very high based on index quintiles). In the center *bar chart*, *dark gray vertical bars* represent the mean of the individual estuary composite stressor index scores within each subregion. *Error bars* represent standard error. *Vertical bars* (subregions) that do not fall under the same *horizontal bar* are significantly different than one another (one-way ANOVA, Tukey's post hoc comparison)

components may more strongly limit composite habitat stress (Fig. 2, Table 3).

Researchers have approached assessments of habitat stress or disturbance in different ways. A common theme to all approaches is the importance of including multiple possible indicators, but the statistical approach used to extract single measures from multiple indicators can vary greatly (Sanderson et al. 2002; USEPA 2007; Halpern et al. 2008; Esselman et al. 2011). We used a robust ranking methodology to determine indicators of relative habitat stress and compress ranked variables into a composite measure of habitat stress. Note that even estuaries with the lowest component and

Table 2 Spearman correlations (upper right) and number of estuaries (lower left) for all pairwise comparisons among the four component indices and the composite stressor index

	Land cover	River flow	Pollution	Eutrophication	Composite
Land cover	–	0.36*	0.49*	0.31*	0.81*
River flow	158	–	0.12	0.21*	0.64*
Pollution	211	156	–	0.17	0.66*
Eutrophication	149	110	151	–	0.61*
Composite	196	157	198	153	–

* $p<0.05$

Table 3 Regression results of the best component variables on the eutrophication component index, examined across all estuary units ("all regions"), or for estuaries from each coast of the USA

Variable	All regions		Atlantic		Gulf of Mexico		Pacific	
	Std β	*p*	Std β	*p*	Std β	*p*	Std β	*p*
% land use in catchment	**0.412**	**<0.001**	0.085	0.586			−0.077	0.795
% change undeveloped in catchment					−0.165	0.269		
% change in estuary shoreline			−0.234	0.068				
Dams/km^2					**−0.758**	**0.001**	**0.585**	**0.006**
Mean annual discharge/km^2	−0.100	0.314	−0.164	0.189	**−0.595**	**0.003**		
Low pulse duration							−0.402	0.066
High pulse duration	−0.159	0.094	**−0.370**	**0.014**				
Trend in 7 weeks max flow			−0.113	0.366				
Pollution sites/km^2	−0.174	0.078	−0.214	0.088	0.455	0.068	−0.163	0.558
R^2	0.381		0.561		0.463		0.234	
n	107		55		27		25	
p	0.001		0.001		0.011		<0.001	

For each regression, whole model R^2, sample size (*n*), and *p* values are reported from consensus regression analysis (see "Methods"), as well as standardized β and *p* values for each component variable included in the model (variables with slopes significantly greater than 0 are in bold

composite stress scores have undergone changes over the last two centuries. Hence, our approach does not necessarily address the absolute extent to which individual estuaries have been impacted by anthropogenic activities. The next step toward a more direct assessment of habitat is to evaluate how component metrics relate with patterns in the distribution, abundance, and production of fish and shellfish. These types of analyses, which have often been done at smaller scales in the context of fish communities (Jordan et al. 2008) or indices of biotic integrity (Deegan et al. 1997) often show nonlinear responses with respect to gradients in environmental characteristics. Therefore, our results likely provide a lower threshold of habitat stress.

The approach we have used is national in scope yet considers an individual estuary as the unit of study, and has the strength of using consistent methods and data across several regions. These two attributes enable comparisons at multiple scales, between estuaries and between regions. To a lesser extent, our approach can also inform planning within estuaries to the extent that such decisions focus on examination of different component indexes and variables contributing to composite scores. Larger estuaries are notable for their habitat heterogeneity, and for these places, composite scores may be less suitable for identifying and prioritizing habitats within them. Nevertheless, the largest estuaries examined in our assessment were often represented by multiple units, and so coarse-scale analysis is still possible using composite and component indicators calculated by this analysis. Within these large systems, the composite stressor index performed relatively well. For example, composite scores in Puget Sound ranked urbanized Central and South Puget Sound more stressed than more rural Whidbey Basin, and this pattern tracks fish abundance and diversity (Rice et al. 2012). Likewise, 15 individual systems within Chesapeake Bay are ranked using the Bay Health Index (IAN 2011), and scores from the composite index positively tracked recent scores (2010) for both the overall index (r=0.37) and the biotic index (r=0.5).

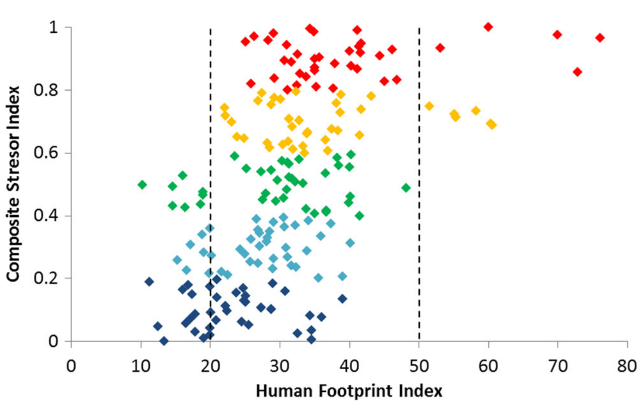


Fig. 4 Relationships between the composite stressor index and the human footprint index within catchments of estuaries. *Colors* indicate various levels of the stressor index as mapped in Fig. 3. *Vertical lines* indicate the approximate position of potential thresholds between human footprint and relative estuarine stress levels

Component Indices

We focused on four component indices of habitat stress: land cover, river flow, pollution, and eutrophication. These components directly relate to major contributions of varied anthropogenic impacts and can be derived from datasets with national coverage. Other stress habitat indicators were not available for the majority of estuaries at this large spatial scale. For example, the EPA National Estuary Program Coastal Condition Report provides water quality assessments for 39 estuaries in the National Estuary Program (USEPA 2007), just 20 % of the total number recognized in our analysis. Other reports from this series use point scores to make comparisons among regions, but do not attribute results to individual estuaries (USEPA 2012).

Land Cover The most comprehensive of the four national indicator datasets was land cover data from NOAA's C-CAP database. Land cover and land cover change provide a record of many of the anthropogenic activities affecting estuary habitat, including but not limited to diking and filling of tidally influenced wetlands (Squires 1992), shoreline hardening (Bilkovic and Roggero 2008), changes in hydrology and sediment delivery (Gregory et al. 1992; Booth and Henshaw 2001), and contaminant and nutrient inputs (Hopkinson and Day 1980; King et al. 2004). The combination of these effects can lead to changes in the quantity and quality of estuarine habitats (Holland et al. 1995). This is evident in our analyses from the strong correlation between a high degree of land cover alteration and low eutrophication, pollution and river flow component scores.

Using land cover data to assess estuarine habitat stress has several advantages, but also some limitations. Data are available for all estuaries in the contiguous USA and incorporate both shoreline and watershed effects of land use. The approach also gives estimates of both current extent and recent land cover change, and provides information on a range of human activities for which may not be directly measurable at a national scale. However, because the dataset focuses on terrestrial changes, the resolution and typology of C-CAP may underestimate some habitat quality changes, particularly in intertidal or subtidal portions of estuaries. In these areas, refining shoreline habitat types (e.g., through detailed mapping systems such as ShoreZone, ConserveOnline 2012) would result in improved understanding of the multiple ways land use influences estuarine habitat. Furthermore, C-CAP focuses on recent land use patterns, and cannot identify legacy effects, except to the extent in which land cover can be classified into classes (e.g., development or agriculture) that were not present presettlement. This was one strategy we used in developing change metrics from the C-CAP data.

Not surprisingly, the land cover component stressor score was high in regions of high population density, such as the Southern California Bight, Southern Florida, and Mid-Atlantic Bight. Likewise, the lowest scores occurred in the relatively low-populated Oregon and Washington and Downeast Maine subregions. However, some high-scoring subregions such as the Northwest Gulf of Mexico and Texas may reflect broad-scale habitat alterations resulting more from intensive agriculture than increases in population density (Table 1).

River Flow The river flow component index is a gage of hydrologic alteration, freshwater input, material recruitment, and inundation potential from freshwater systems. Our index incorporated metrics related to duration of high and low flow events; average-, high-, and low-flow magnitudes; their change over multiple decades; and the potential effects of dams within the watershed. Our results indicated that flow scores were strongly related to land use and eutrophication, and that eutrophication in different regions was dissimilarly sensitive to component flow variables.

However, because this component score is available only where the USGS has flow gages with extensive time series, it had the second highest number of data gaps. Variation in flow is a combination of both natural variation resulting from precipitation patterns and geomorphology (Olden and Poff 2003), as well as anthropogenic influences such as hydropower and flow diversion (Nilsson et al. 2005), groundwater use (Sophocleous 2002), and land use activities (Hammer 1972). Our finding that the river flow component stressor index was high in places like the Southern California Bight and low in the Salish Sea likely reflects natural variation in regional precipitation patterns that translate into characteristic flow signatures to some degree (Olden and Poff 2003). Nevertheless, the strong correlation between river flow and land cover component scores (Table 2) suggests that land use alterations can have dramatic effects on river flow patterns.

Pollution This component indicator described point source contaminants in watersheds feeding estuaries. The pollution index was developed from four national databases on point sources and was available for all but one estuary within our framework. The index accounts for the density of sites within a watershed, but does not account for potential dilution and distribution of contaminants, which would be determined by river flow, currents, quantity of pollutants, proximity of spills to flowing water, and residence time. In addition, the index likely ignores the legacy of older point sources and is focused on chemical, rather than nutrient, pollutants. Pollution data within estuaries has been nationally measured for a much smaller subset of estuaries through the Environmental Protection Agency's Environmental Monitoring & Assessment Program (EMAP), and the pollution component index compared favorably with some of the pollution metrics derived via EMAP sampling within estuaries. Our pollution component stressor index positively correlated with the land use component index, and was lowest along the coast of Central California, Oregon and Washington, and highest in Southern New England, the Southern California Bight, and Mid-Atlantic Bight.

Eutrophication This component metric, based on data from NOAA's NEEA (Bricker et al. 1999, 2007), captures processes that can lead to eutrophication in estuaries. These conditions—high temperature, elevated nitrogen or phosphorous inputs, and long water residency—fuel algal blooms and die-offs, spikes in microbial respiration, and resultant declines in dissolved oxygen (Rabalais 2002; Rabalais et al. 2002; Hagy et al. 2004). This combination can lead to fish kills and regional "dead zones" (Paerl et al. 1998; Thronson and Quigg 2008; Quigg et al. 2009; Craig 2012). This dataset is valuable because it focuses on conditions within the estuary, rather than in its catchment. However, it is also the component with the most gaps in spatial coverage. The eutrophication component index exhibited strong differences across subregions, with the Mid-Atlantic Bight, Salish Sea, and Southern Florida at high threat of eutrophication compared to coastal Oregon and Washington.

We found that the eutrophication component index significantly correlated with both land cover and river flow indices, but that the relative influence of land cover and river flow was scale-dependent. At the largest scale (the contiguous USA), our findings that the total agricultural and development-related land use within an estuary's local catchment was the primary predictor of eutrophication symptoms corroborate other work documenting numerous potential anthropogenic causes of eutrophication (Paerl et al. 1998; Valiela and Bowen 2002; Fisher et al. 2006; Rabalais et al. 2010; Golden and Knightes 2011). However, regionally-specific patterns of climate, land use, and water use likely resulted in the greater influence of river flow variables when eutrophication was examined within each coast. Previous work has documented the importance of hydrologic patterns for both ameliorating and exacerbating eutrophication (Paerl et al. 1998; Hagy et al. 2004; Rabalais et al. 2010; Murphey et al. 2011). Timing, duration, and intensity of river flow in the context of local organic loadings likely determine the overall influence of flow on eutrophication (Paerl et al. 1998), and is likely why river flow variables gained importance at more local levels. Overall, our results indicate that the degree of eutrophication reflects the ways in which people alter terrestrial inputs (through land use), freshwater parameters such as temperature, and river flows that deliver inputs to estuaries, mediated by local controls such as bathymetry and residence time (Cloern 2001).

Applications

Increasingly, scientists are examining catchment linkages with habitat and food web components of estuarine and marine systems (e.g., Hagy et al. 2004; King et al. 2004; Halpern et al. 2008). In this paper, we evaluated the utility of using a combination of freshwater-based and direct estuarine predictors of habitat stress, and found that freshwater-based indices of river flow and land cover exhibited significant correlations with eutrophication measured in estuaries. The eutrophication component index has the most data gaps of the four component indices, so the other three indexes developed here are useful in providing a more robust description of habitat stress, particularly for those areas lacking data on eutrophication. More generally, the entire set of component variables can inform other catchment contributions to estuarine habitat stress.

Together, the component indices and composite index of habitat stress should be useful in regional and subregional habitat evaluations and prioritization efforts toward habitat protection, restoration, and remediation. Examination of the relationship of our composite scores with the HFI (Fig. 4) suggests that these choices might vary with respect to intensity of anthropogenic impacts. At relatively low levels of human influence (HFI <20 %), efforts might be more focused on habitat protection and restoration of habitat-forming processes. At high levels of influence (HFI >50 %), many habitat-forming processes are likely constrained by urbanization, and strategies that focus on mitigation and education may be most relevant. Between these levels, the resilience of estuary habitats to human impacts may be highly variable and depend greatly on regional variation, estuary size, and habitat heterogeneity within estuaries. Partnerships of national and local groups can help better resolve how local differences contribute to habitat condition. The National Fish Habitat Partnership (NFHP), a coalition of federal and state agencies, academia, and nongovernmental organizations, supports regional partnerships to restore and protect fish habitat as well as national synthesis efforts to scientifically inform this process (NFHAP 2006; NFHP 2009; National Fish Habitat Board 2010). Our analysis provides insight into the national effort by documenting broad patterns of threats to estuary habitats, and will therefore facilitate conservation planning and additional research among individual estuary systems.

Future Efforts

This assessment provides insight into the status of US estuaries at a broad spatial scale. Future efforts will help refine this assessment to improve our conclusions about estuary habitat at finer spatial scales. Because they include salinities ranging from fresh to marine, estuaries comprise complexes of different ecological communities, and these communities likely exhibit different responses to habitat stressors. NOAA's spatial framework includes some delineation of mixing zones, but these zones are not directly tied to estuarine habitat typologies (e.g., scrub-shrub systems, salt marshes, and mudflats) per se. As we compiled information on potential indicators of habitat stressors, we were struck by the patchwork nature of datasets. Some of the most comprehensive datasets (river flow and eutrophication) have notable spatial gaps. Other extremely useful datasets that have been used to characterize estuary habitat such as Shorezone (ConserveOnline 2012) are specific only to particular regions. Hence, a combination of improving the spatial resolution and coverage of habitat datasets will likely enhance the ability both to predict how estuary habitat changes in response to anthropogenic stressors, and to prioritize local habitat restoration and conservation efforts.

Future efforts also should incorporate biological responses. Habitat is defined by the species that use it, and therefore efforts to assess habitat stressors will be greatly improved by examining responses of fish and shellfish. The habitat stressors we used in this study have been shown to influence estuarine fish assemblages (Cross and Williams 1981; Polgar et al. 1985; Limburg and Schmidt 1990; Vasas et al. 2007). However, the existence of different estuarine species in different regions of the USA calls for either analysis of functional groups across regions (e.g., feeding guilds, salinity preferences, species differing in life stages that use estuaries), or region-specific analyses of relationships between fish and habitat stressors. Ongoing national efforts to incorporate biological responses of fish will reveal the degree to which ranges of habitat stressors translate to status and availability of areas used by fish communities, and thereby shed more light on the status of estuary habitats across the USA.

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Appendix 1

Table 4 Variables contributing to the four component indices, and hypothesized impact of anthropogenic change on variables ("+" indicates human influence will result in an increase in the variable; "–" indicates a resultant decrease)

Variable	Units	Direction of anthropogenic change	Description
Land cover			
Agriculture—estuarine shoreline	m^2	+	Includes cultivated and pasture/hay 2006 C-CAP land cover classes
Agriculture—watershed	m^2	+	Includes cultivated and pasture/hay 2006 C-CAP land cover classes
ΔEstuarine—estuarine shoreline	m^2	–	Change in estuarine forested wetland, estuarine scrub/shrub wetland, estuarine emergent wetland, and estuarine aquatic bed 2006 C-CAP land cover classes from 1996 to 2006
ΔEstuarine—watershed	m^2	–	Change in estuarine forested wetland, estuarine scrub/shrub wetland, estuarine emergent wetland, and estuarine aquatic bed 2006 C-CAP land cover classes from 1996 to 2006
Developed land cover intensity—estuarine shoreline	m^2	+	Includes [density factors are in parentheses] high intensity developed (2.5), medium intensity developed (1.5), low intensity developed (1.0), and developed open space (1.0) 2006 C-CAP land cover classes. Represented as a density-weighted score reflecting development using the density factors listed above
Developed land cover intensity—watershed	m^2	+	Includes [density factors are in parentheses] high intensity developed (2.5), medium intensity developed (1.5), low intensity developed (1.0), and developed open space (1.0) 2006 C-CAP land cover classes. Represented as a density-weighted score reflecting development using the density factors listed above.
ΔPalustrine—estuarine shoreline	m^2	–	Change in paulustrine forested wetland, palustrine scrub/shrub wetland, palustrine emergent wetland, and palustrine aquatic bed C-CAP land cover classes from 1996 to 2006.

Table 4 (continued)

Variable	Units	Direction of anthropogenic change	Description
ΔPalustrine—watershed	m^2	−	Change in paulustrine forested wetland, palustrine scrub/shrub wetland, palustrine emergent wetland, and palustrine aquatic bed C-CAP land cover classes from 1996 to 2006.
ΔUndeveloped—estuarine shoreline	m^2	−	Change in deciduous forest, evergreen forest, mixed forest, grassland, and scrub/shrub C-CAP land cover classes from 1996 to 2006.
ΔUndeveloped—watershed	m^2	−	Change in deciduous forest, evergreen forest, mixed forest, grassland, and scrub/shrub C-CAP land cover classes from 1996 to 2006.
River flow			
Dam density	Dams/km^2	+	Density of dams in an estuary's entire watershed.
Mean annual discharge (MAD)	m^3/s	−	Average flow across the entire year, averaged across the 15 most recent years of data and divided by watershed drainage area.
7-Day minimum discharge	m^3/s	−	Average flow during the seven consecutive lowest-flow days in a year, averaged across the 15 most recent years of data and divided by MAD.
7-Day maximum discharge	m^3/s	−	Average flow during the seven consecutive maximum flow days in a year, averaged across the 15 most recent years of data and divided by MAD.
Low pulse duration	Days	+	Average number of consecutive days of low flows (<25 % percentile of daily flow), averaged over the most recent 15 year of data.
High pulse duration	Days	−	Average number of consecutive days of high flows (<75 % percentile of daily flow), averaged over most recent 15 years of data.
Trend in 7-day minimum discharge	m^3/s/year	−	Linear coefficient of the trend in 7-day minimum discharge over entire annual time series.
Trend in 7-day maximum discharge	m^3/s/year	−	Linear coefficient of the trend in 7-day maximum discharge over entire annual time series.
Trend in low pulse duration	Days/year	+	Linear coefficient of the trend in low pulse duration across the entire annual time series.
Trend in high pulse duration	Days/year	−	Linear coefficient of the trend in high pulse duration across the entire annual time series.
Pollution			
Mines and mineral processing plants	Mines/km^2	+	US mines and mineral (metals) processing plants active in 2003 and monitored by the National Minerals Information Center of the US Geological Survey (USGS 2005)
Toxic release sites	Sites/km^2	+	Facilities that reported the release of toxic chemicals to the USEPA Toxics Release Inventory in 2007 (USEPA 2010)
Pollution discharge permits	Permitted facilities/km^2	+	Facilities with USEPA regulated National Pollution Discharge Elimination System point source pollution permits in 2007 (USEPA 2010)
Hazardous waste sites	Sites/km^2	+	Sites of known releases or threatened releases of hazardous substances, pollutants, or contaminants on the USEPA's Superfund National Priority List as of 2007 (USEPA 2011)
Eutrophication			
Overall eutrophic condition	n/a	+	Overall eutrophic condition (OEC) index from the National Estuarine Eutrophication Assessment.

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