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Lost and found coastal wetlands: Lessons learned from mapping estuaries across the USA

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ABSTRACT

Conservation of estuaries is strengthened by an understanding of past and current estuary extent, which helps stakeholders envision resilient estuarine habitats in the future. We used spatial analyses to improve understanding of estuarine habitat and extent in and around 30 US National Estuarine Research Reserves using two approaches, elevation-based mapping and historical mapping. We collaborated with stakeholders to incorporate local knowledge, and found that our methodologies were effective across disparate geographies. Elevation-based mapping proved to be a powerful tool for mapping areas within reach of tides, yielding a better understanding of the past, present, and potential estuary. This approach revealed that US estuaries are or were bigger – often vastly so – than what is shown in most maps. In particular, at over 80 % of studied estuaries, elevation-based mapping detected temperate forested tidal wetlands missed by maps generated primarily from aerial photographs. Historical mapping, conducted consistently across diverse regions, provided a valuable window into past ecological conditions. Our change analysis using historical maps revealed that tidal marsh has undergone dramatic losses on the Pacific coast (average > 60 % loss). On other US coasts, tidal marsh extent has changed less (average < 10 % loss), with marsh losses offset by landward migration; however, marsh migration may have caused net loss of vegetated tidal wetlands due to loss of forested tidal wetlands. Comparing mapping methods revealed important changes that could not be detected using a single method. Each mapping approach had limitations, so combining multiple methods will enhance understanding of both past and present conditions at estuaries worldwide.

1. Introduction

Estuaries – where land, rivers, and sea meet – are naturally dynamic and influenced by multiple drivers of change. They have long been centers of human populations, which benefit from shallow waters that provide natural harbors, seafood, and fertile wetland soils that can be farmed productively (Kennish, 2023). Due to these historical pressures, estuaries are considered the most anthropogenically degraded ecosystems on earth (Edgar et al., 2000). Intact estuarine habitats provide ecosystem services such as shoreline protection and carbon sequestration, and serve as nurseries for commercially valuable fish and invertebrates (Barbier et al., 2011; Beck et al., 2001; Mcleod et al., 2011). In a changing climate that includes accelerated sea-level rise, estuarine habitats and their services are at risk (Crosby et al., 2016; Passeri et al., 2015). There is thus an urgent need for estuarine restoration to address past degradation, and for climate adaptation planning

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for the future (Waltham et al., 2021).

Mapping estuarine habitats is a critical part of designing coastal conservation and restoration strategies to protect their services. Mapping the current extent of estuaries is needed for protecting habitat from development, and for planning migration pathways in the face of rising seas. Mapping of estuary extent is typically accomplished through interpretation of aerial photographs. In the US, the US Fish and Wildlife Service (USFWS) uses such imagery for its National Wetland Inventory (NWI), the best resource for consistent nationwide maps of current estuary extent. Brophy et al. (2019) developed an alternative estuary-mapping approach using tide heights and topography, which they thoroughly ground truthed and successfully implemented on the conterminous US Pacific coast. Advantages of the elevation-based approach include its derivation from first principles (estuary boundaries are defined by tidal inundation) and its objectivity, consistency and replicability across diverse estuarine landscapes.

Mapping the past extent of estuaries is also vital for informing management. Change analyses comparing past to present can shed light on mechanisms of change and restoration opportunities, such as identifying former estuarine wetlands now disconnected by dikes, which could be reconnected in the future. Understanding past estuarine extent also informs climate change planning, since areas where tides have been restricted may be flooded again as sea levels rise. The traditional approach for understanding the past extent of estuaries is to use historical maps. US coasts were surveyed in the 1800s and 1900s by the US Coast and Geodetic Survey, resulting in detailed topographic maps ("T-sheets"). These T-sheets have been used extensively in California (Grossinger et al., 2011; Stein et al., 2010, 2020) to inform estuarine habitat management goals, but have not been applied at most estuaries in other regions. The T-sheets (also called "historical maps" herein) provide robust insight into past tidal habitats and their extent, with the caveat that they focus on the lower estuary, especially shorelines and tidal marsh. Distinctions between forested tidal wetlands (also called "tidal forests"), scrub-shrub tidal wetlands, and nontidal wetlands were not consistently made, which limits our ability to map the full historical extent of estuaries using historical maps alone. Elevation-based mapping provides an alternate approach by estimating the area within reach of tides today, which, barring major changes to elevation or water levels, should approximate that area in the past. Elevation was effective as a proxy for past conditions at many West Coast estuaries and compared favorably with historical mapping in areas of overlap (Brophy et al., 2019). Elevation-based mapping is useful because it defines the area that would be within reach of the tides, in the absence of anthropogenic tidal flow barriers such as dikes and tide gates. Since most of those anthropogenic tidal flow barriers were built after European colonization, elevation-based mapping can be used to define the estuary extent immediately prior to European colonization. Nonetheless, elevation-based mapping sometimes fails to capture areas that were historically part of the estuary – either due to the dynamic nature of the estuary (e.g. deposition, dunal movement), anthropogenic activity (e.g. fill, subsidence), or errors in digital elevation models.

We mapped past and present distributions of estuarine habitats in and around the 30 estuaries associated with the US National Estuarine Research Reserve System (NERRS), a partnership between the National Oceanic and Atmospheric Administration (NOAA) and agencies in each coastal state. The NERRS provides an ideal platform for conducting investigations that are locally relevant and can also form the basis of syntheses of the status of national trust resources (Raposa et al., 2016; Stevens et al., 2023; Wasson et al., 2019). At the local level, our objective was to provide individual Reserves with urgently-needed and powerful new maps to support their restoration, conservation, and climate adaptation planning. At the national level, we applied consistent methods across 30 Reserves and surrounding estuaries on all US coastlines, Alaska, Hawaiʻi and Puerto Rico, to accomplish our objectives of evaluating overarching trends and regional differences and supporting national strategic planning for coastal resilience.

We consistently applied elevation-based and historical mapping approaches, and compared these to each other and to maps generated by NWI. This is the first rigorous examination of these mapping methodologies across such a broad geographic scope – including diverse estuary types across 24 US states, ranging in latitude from approximately 18 to 60 degrees. We evaluated the effectiveness of the mapping approaches across these varied estuaries, by testing their applicability and identifying strengths and weaknesses. For elevation-based mapping, we determined whether mapping the area within the potential reach of tides effectively detected parts of the current estuary missed by NWI and areas of the former estuary missed by historical mapping, and where possible, we conducted a change analysis. For historical mapping, we characterized the distribution of habitats at one point in the past, and where possible analyzed change in comparison with a more contemporary time point, with emphasis on tidal marsh. Our recommendations inform future estuarine mapping anywhere in the world. We concur that in the face of climate change, historical ecology and mapping is critical "to create forward-looking management strategies that are rooted in place and past" (Beller et al., 2020). Accurately characterizing the past, the present, and change helps us plan for the future.

2. Methods

We used a two-pronged approach to mapping estuaries, applying both elevation-based and historical mapping (Table 1). Each approach is described separately below, followed by a section detailing how the results of these two approaches were compared. We used both approaches to shed light on less-altered baseline conditions for the estuaries. While humans have been interacting with coasts for millennia (Scarborough et al., 2022), major modifications such as extensive diking, draining, filling of wetlands mostly occurred well after European colonization. We thus attempted to characterize past conditions before major modifications to hydrology (but noted where substantial anthropogenic changes predated the historical maps). To characterize present conditions, we used the most recently updated maps generated by NWI.

We conducted this analysis at the estuaries surrounding the 30 National Estuarine Research Reserves (Fig. 1). The description of methodology below focuses on the 28 tidal estuaries; the methodology was modified for the two Great Lakes Reserves. Using field surveys or local Reserve habitat maps, a local contact at each Reserve evaluated whether particular areas were estuarine or not (where elevation-based mapping and NWI yielded different results), and helped interpret accuracy of the

Table 1
Comparison of mapping approaches.
This table summarizes methods as applied to the 28 tidal estuaries; methods were modified for the two Great Lakes estuaries (Appendix A, Sections 2–3).

Approach	Method for identifying tidal wetlands	Time period
Elevation-based mapping	Areas that should be within range of highest annual tides based on their elevation: areas below 50 % exceedance contour extrapolated from NOAA's Extreme Water Level stations	Past and present
National Wetlands Inventory	Areas classified by NWI as either *Saltwater Tidal* or *Freshwater Tidal*. NWI maps are based primarily on visual assessment of aerial imagery.	Present
Historical mapping	Areas classified in T-sheets as tidal either based on their habitat symbology (salt marsh, tidal flat, salt panne, tidal creek, etc.) or because they are shown below the landward limit of tides (generally defined as the mean high tide line). Based on topographic surveys and hand-drawn maps.	Past

Note that for all three approaches, **tidal wetlands** include both estuarine and freshwater tidal habitats, both vegetated and unvegetated habitats, and both intertidal and subtidal habitats. Vegetated intertidal habitats include emergent, scrub shrub, and forested tidal wetlands.

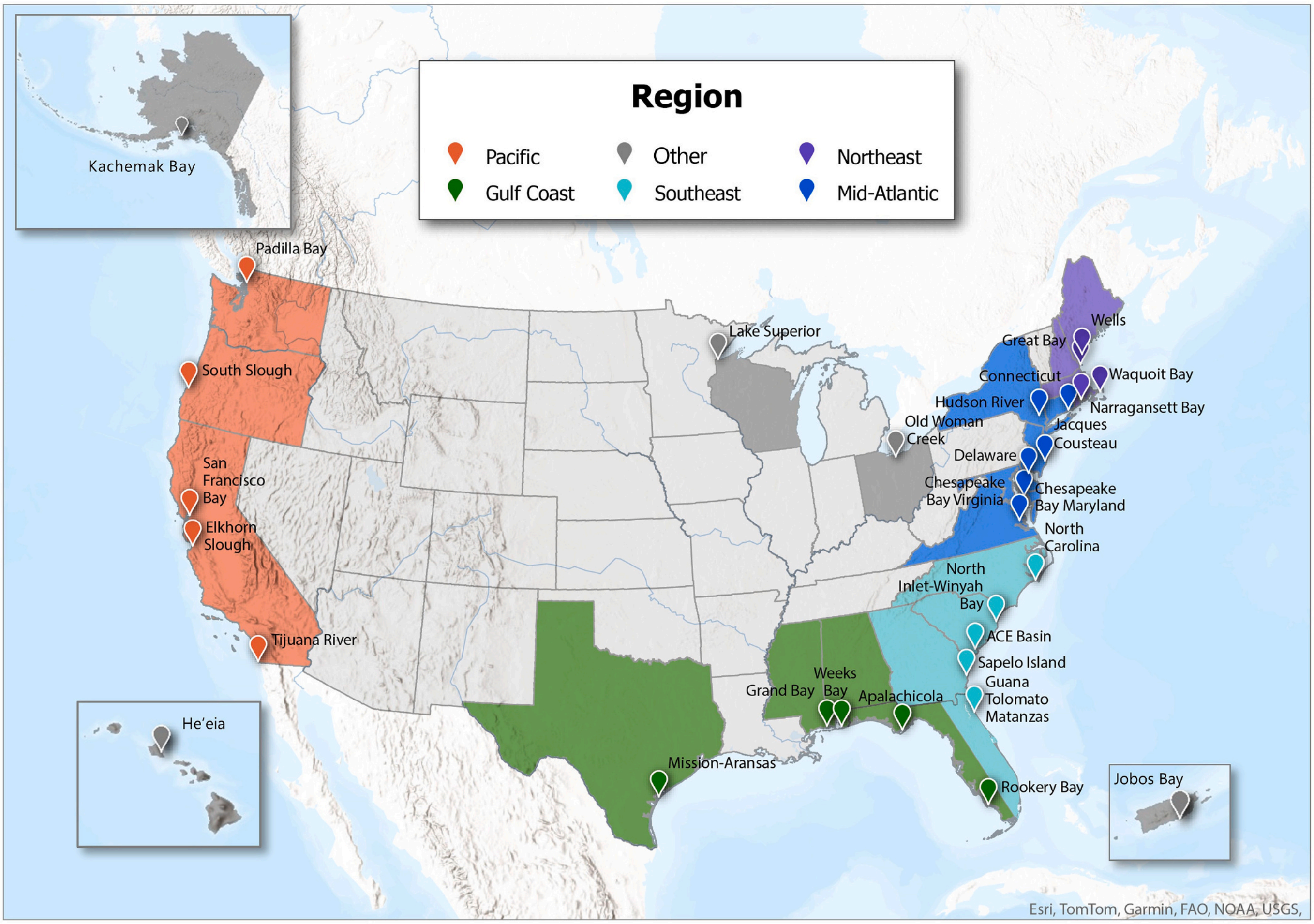

Fig. 1. Map of the 30 National Estuarine Research Reserves.
The 25 tidal estuaries in the contiguous US are shown color-coded by region, corresponding to colors in later figures. The five estuaries in the "Other" category shaded in gray are non-tidal estuaries (i.e., the Great Lakes) or outside the contiguous US.

map of the past estuary based on historical documents or local knowledge.

In addition to assistance from these Reserve contacts, the project benefited from a team of Mapping Advisors, who provided technical guidance, regional data sources and local ground truthing. An Advisory Committee assisted with the development of outreach products, in an iterative collaborative process (Appendix A, Section 1). All resulting maps and products are publicly available (Endris et al., 2024).

2.1. Elevation-based mapping

2.1.1. Mapping area within reach of tides

Estuary extents are defined as areas subject to tidal inundation (Wolanski and Elliott, 2015). We used NOAA-generated digital elevation models (DEMs) combined with high-water-level datums to find the annual high-tide contour on the landscape. Areas below this contour represent the likely extent of the estuary, in the absence of tidal flow barriers such as dikes or water control structures (Brophy et al., 2019). This contour is also useful to map past estuary extent prior to construction of such barriers. In most regions, we mapped annual high tide using the 50 % annual exceedance elevation from NOAA's Extreme Water Level analysis, which has been ground truthed for the US West Coast and corresponds well to the upper boundary of tidal wetlands (Brophy et al., 2019). This contour is also useful to map past estuary extent prior to construction of such barriers. For US Northeast coast estuaries (North Carolina to Maine) we used the Army Corps of Engineers North Atlantic Coast Comprehensive Study (NACCS) (biennial recurrence) as a source for annual high water levels. This dataset includes over 16,000 points representing storm surge, wave heights, and extreme water levels derived from numerical model runs. The data matches well with nearby NOAA water level stations and provides much higher-resolution data. We confirmed with each Reserve contact that the 50 % exceedance or NACCS annual recurrence water level approximated the annual high tide or "king tide" in their area. We mapped areas below these annual high water levels within one or more contiguous Hydrologic Unit Code (HUC) watershed units of the United States Geological Survey (USGS) surrounding each Reserve, resulting in a total area of 6743 km^2 across the 28 tidal Reserves, excluding subtidal area. For the Great Lakes estuaries, we used historical water level data, averaged monthly at the nearby NOAA water level stations, to determine an appropriate flood level elevation. For all Reserves, we mapped the area below the annual high tide or flood level elevation using local bare-earth Light Detection and Ranging (LIDAR) datasets (details in Appendix A, Section 3).

2.1.2. Comparison to NWI

We compared the elevation-based estimate of current estuary boundaries described above to that provided by NWI (including both estuarine and freshwater tidal; Table 1). We used the most recently updated NWI for each Reserve, which ranged from 1970s–2020s. Within the total area identified as estuarine habitat by either method, we quantified the area shown only in the elevation-based map ("elevation-only"), the area shown only in NWI ("NWI-only"), and the area of overlap across both maps ("both"). With the help of local ground truthing, we answered the following four questions for each estuary: 1) Are some of the "elevation-only" areas currently estuarine habitats? 2) Are some of these areas tidal forests? 3) Are some of the "elevation-only" areas former or modified estuarine habitats? 4) Are some of the "NWI-only" areas currently estuarine habitats? We tallied the affirmative answers to these questions for a national synthesis of effectiveness of the approaches. (This comparison between estuarine habitat identified by elevation versus NWI could not be made at the Great Lakes, because NWI does not have a habitat class for lake estuarine habitat. Instead, we simply examined whether NWI identified the elevation-based mapping area as wetland.)

2.1.3. Change analysis

At many estuaries, neither water levels nor land elevations have changed substantially (>1 m) over the past two centuries. Therefore, elevation-based mapping can often provide a good estimate of the past estuary boundary (Brophy et al., 2019). We ground-truthed this estimate in the area of the estuary that was the focus of historical mapping (see Section 2.3). Where possible, we conducted a change analysis by quantifying the difference between the elevation-based map as an estimate of the past estuary, and NWI mapping of the current estuary. Specifically, we defined nontidal wetlands identified by NWI or other areas within the elevation-based mapping that are absent from NWI as "Former Tidal Wetlands." This change analysis was considered robust only for estuaries where elevation-based maps and NWI were deemed to provide reasonably accurate data on past and present boundaries, respectively. At seven estuaries, consultation with local experts suggested both conditions were met, and we conducted a change analysis. For the other 21 tidal estuaries, differences between elevation-based maps and NWI did not represent change, but instead were artifacts of inaccurate NWI mapping of current conditions (see Section 3.1). At one estuary (Tijuana River Reserve on the urbanized US / Mexico border), NWI was so substantially inaccurate that we used a local Reserve habitat map instead of NWI to characterize the present. Since the proportion of unvegetated tidal wetlands and waters (i.e. estuarine channels, bays, and mudflats) can vary considerably across different estuaries, we summarized the final results in two ways: percent change in total area of tidal wetlands and waters compared to historical conditions; and percent change in tidal wetland area for areas presumed to have been historically vegetated (i.e. excluding unmodified, unvegetated tidal wetlands and waters) (details in Appendix A, Section 3).

2.2. Historical mapping

2.2.1. Historical maps

Between 1834 and 1980, topographic maps (T-sheets) were created for most of the US coast by the US Coast Survey. Lake surveys were created for the Great Lakes between 1841 and 1882 by the Bureau of Topographical Engineers of the War Department. Early T-sheets provide accurate data on the location and diversity of habitats such as tidal channels, mudflats, and tidal marshes inside US estuaries before the most substantial human alterations to tidal hydrology; lake surveys depict lacustrine and palustrine habitats. We worked with Reserve contacts to select the oldest available color map that could be interpreted to examine extent and distribution of habitats in their selected area of interest on or near each of the 30 Reserves. The selected T-sheet and lake survey dates ranged from 1842 to 1926, early enough to provide useful information on historical habitats, although alterations had already occurred in some areas, particularly those colonized earliest (details in Appendix A, Section 4 and Appendix B).

High resolution color scans of the T-sheets and lake surveys were obtained from NOAA's online Historical Map & Chart Collection or ordered from the National Archives. T-sheets were mapped at a scale of 1:10,000 to 1:20,000 except Alaska, at 1:40,000. The lake surveys were mapped at 1:32,000 and 1:80,000. The average area of the T-sheet analyzed was 14,000 ha (range 491–84,763 ha). T-sheets surveyed before 1927 used US Standard Datum reference and most had been updated with North American Datum, 1927 (NAD27) marks. Surveys that had not been updated were transformed to NAD27 using the NOAA National Geodetic Survey (NGS) Coordinate Conversion and Transformation Tool. All maps were then transformed to NAD83, adjusted using permanent landmarks visible on current aerial images and/or NGS marks, and projected into local UTM coordinate zones (Grossinger et al., 2011) (details in Appendix A, Section 4).

Polygon representations of the historical map features were on-screen digitized in ESRI ArcGIS Pro (scale 1:2000). T-sheet legends (also applicable to lake surveys) were used to classify the habitat features and were assigned an NWI Classification code (Cowardin, 1979). Areas were classified as tidal based either on their habitat symbology or because they were shown below a line representing the landward limit of tides, generally defined as the mean high tide line (Shalowitz, 1962). The T-sheets did not have clear symbology for shrub/scrub or aquatic beds (submerged aquatic vegetation), so these were not separately identified (details in Appendix A, Section 4 and Appendix B).

2.2.2. Characterizing change

To visualize changes in broad habitat categories, the historical and current habitat data were grouped into five general classes. We compared the historical map to NWI to characterize change at each Reserve with two exceptions, Great Bay and Tijuana River (see Section 4, Appendix A). We qualitatively summarized the most obvious patterns of change, highlighting estuarine habitats that had undergone the most loss. Areas that remained uplands and areas that remained subtidal from past to present were omitted. Additional details, including methods used for the two Great Lakes estuaries and details on habitat classes, are available in Appendix A, Section 4.

At five tidal Reserves, we conducted a more detailed quantitative habitat change analysis, as a proof-of-concept of the power of using historical maps. We analyzed change for each major habitat type, focusing on estuarine wetland change and including uplands that transitioned to or from tidal wetlands. We summarized changes in tabular format and used Sankey diagrams (Spencer, 2022) to illustrate transitions among habitat categories. We also conducted a detailed change analysis at one Great Lakes Reserve. (See Appendix A.) The estuaries selected for these more detailed analyses spanned diverse geographic regions and were ones where core co-authors worked, and thus could verify both past and present mapping with additional data sources. At two of these Reserves, we used an alternative to NWI to better characterize present conditions: a local habitat map generated by the NERR for Tijuana River Reserve in California, and a Coastal Change Analysis Program (CCAP) map from NOAA for Great Bay Reserve in New Hampshire.

Where possible, we estimated change in estuary extent by comparing the historical map and NWI. These calculations were made only at the 13 tidal Reserves where the historical maps and NWI were considered reasonably accurate estimates of past and present estuary extent, respectively. At the majority of Reserves (17 of 30), differences between the historical maps and NWI were artifacts of different classification methods or scopes of mapping effort. For example, T-sheet surveyors did not always map tidal and nontidal forested wetlands. In some cases, this led to underestimation of loss when these habitats were converted to other land uses such as agriculture; in other cases, current tidal forests appeared as spurious "gains" due to their omission from T-sheets. For the Great Lakes, we were unable to conduct this change analysis because NWI does not map estuarine habitat in Great Lakes estuaries.

Tidal marshes were accurately mapped in both historical maps and NWI at most tidal estuaries; exceptions were three estuaries where little or no tidal marsh was mapped historically (the Reserves in Oregon, Hawaiʻi, and Alaska) and one where some tidal marshes were missed by historical mapping, according to the Reserve contact (Rhode Island). We thus were able to conduct an analysis of change in tidal marsh extent (within the T-sheet area) at 24 of the 28 tidal estuaries.

2.3. Combining elevation-based and historical mapping

We compared historical mapping and elevation-based mapping within the area of the historical map. Focusing only on total area identified as estuarine habitat, and excluding subtidal habitat or water bodies present in both and unchanged, we quantified the area shown only in the historical map, the area shown only in the elevation-based map, and the area of overlap across both maps (all expressed as percent of total joint area from both methods). We used input from Reserve contacts and ground truthing to determine whether elevation-only areas and historical-map-only areas were likely to have been correctly identified as past estuarine habitats.

We also quantified the difference in estuary extent generated by these two methods versus that present in the same area in NWI, as an estimate of change in estuarine habitat area in this small subset of the estuary. With help from the Reserve contact, we determined whether these change estimates were likely to be robust (that is, if estimates of past and present estuary extent were deemed reasonably accurate). At 18 % (5/28) of tidal estuaries, both estimates were considered robust; at 54 % (15/28) one was robust; and for 29 % (8/28) of estuaries, neither estimate was robust (Appendix C). We averaged robust estimates to quantify change within each estuary, across estuaries and by region. Since NWI does not map estuarine habitat in Great Lakes, we could not conduct this change analysis using NWI for present estuary extent.

All boxplots presented in the Results were generated in R (R Core Team, 2019) using the ggpubr package (Kassambara, 2020).

Table 2

Comparison of elevation-based and NWI mapping across the larger HUC watersheds associated with the 28 tidal US National Estuarine Research Reserves.

The first column lists the geographic region, the second the Reserve. The third column shows the percent of the joint estuary area that was identified as estuarine habitat by both elevation-based mapping and NWI. The fourth column shows the percent identified only by elevation. The following three columns indicate whether this elevation-only ("*E*-only") area includes current estuarine habitats, areas that are former or modified estuarine habitats, and tidal forests, as determined by local expertise or data. The penultimate column has the percent of the area identified only by NWI; the final column indicates whether any of this NWI-only area includes current estuarine habitat as determined by local expertise or data. Darker shading represents higher numbers. The final rows show the averages or percentages across all 28 tidal estuaries. See Appendix C for a more detailed version of this table.

Region	National Estuarine Research Reserve associated with estuary	Both Elevation and NWI	Elevation only ("E-only")	E-only includes current estuarine habitats	E-only includes former or modified estuarine habitat	E-only includes tidal forests	NWI only	NWI-only includes current estuarine habitats
Pacific	Padilla Bay	14	86	X	X	X	1	
	South Slough	26	73	X	X	X	2	
	San Francisco Bay	24	75		X		1	
	Elkhorn Slough	38	61		X		1	
	Tijuana River	51	5	X			44	
Northeast	Wells	67	2	X	X	X	31	X
	Waquoit Bay	62	25	X	X	X	13	X
	Great Bay	80	11	X	X	X	10	X
	Narragansett Bay	65	29	X	X	X	6	
	Connecticut	63	25	X	X	X	12	X
Mid-Atlantic	Hudson River	56	34	X	X	X	10	
	Jacques Cousteau	80	18	X	X	X	1	
	Delaware	89	10	X	X	X	2	X
	Chesapeake Bay VA	85	11	X	X	X	4	
	Chesapeake Bay MD	73	27	X	X	X	1	
Southeast	North Carolina	62	16	X	X	X	23	X
	North Inlet-Winyah Bay	78	19	X	X	X	3	X
	ACE Basin	79	20	X	X	X	2	X
	Sapelo Island	95	4	X	X	X	1	
	GTM	83	12	X	X	X	5	
Gulf	Apalachicola	28	64	X	X	X	8	X
	Rookery Bay	82	15	X	X	X	3	X
	Weeks Bay	40	19	X		X	42	X
	Grand Bay	68	22	X	X	X	10	X
	Mission-Aransas	39	13	X	X		47	X
Beyond contiguous US	He'eia	77	3	X	X	X	20	X
	Kachemak Bay	75	4	X			21	
	Jobos Bay	48	4	X	X	X	48	X
Average across all estuaries		62	25				13	
Percent of estuaries				93%	89%	82%		54%

3. Results

The results are summarized broadly across all 30 estuaries in Tables 2–3 with additional detail in Appendix C. Detailed analyses for all 30 estuaries are summarized in 30 technical reports. Additional products were developed for stakeholders based on input from a project Advisory Committee (Appendix A, Table A.1), including two-page project briefs, color-scanned raster historical maps, 30 Reserve geodatabases in local coordinates, an ArcGIS Online database, a guided tour of national and Reserve-level results in the form of a StoryMap, an interactive web application, and recordings of webinars summarizing the project and detailing the methods used. All products can be accessed via www.nerra.org/estuary-change. Below, we highlight broad patterns and use selected examples to illustrate typical regional trends, and strengths and weaknesses of the methods we used.

3.1. Elevation-based mapping

3.1.1. Elevation-based map versus NWI

The estuary as identified by elevation was typically larger than that identified by NWI (Table 2). The percent of the estuary identified only by elevation averaged 25 % across the 28 tidal estuaries, ranging from 2 % around Wells Reserve in Maine to 86 % around Padilla Bay Reserve in Washington. Overall, the elevation-only area was much greater in the Pacific than in other regions (Figs. 2A, 3). On the Pacific coast, most of the area not in NWI represents lost estuarine habitat (discussed in the next section); in other regions, this area was a mix of current estuarine habitat not identified as such by NWI, and lost estuarine habitat. At 93 % (26/28) of the tidal estuaries, local expertise and ground truthing indicated that elevation-based mapping correctly identified some current estuarine habitat not classified as such by NWI.

Table 3
Comparison of elevation-based and historical mapping within the area of a single historical map in or near each of the 30 US National Estuarine Research Reserves.
The first column lists the geographic region, the second the Reserve. The third column has the percent of the area jointly identified as estuarine habitat by both elevation-based and historical mapping. The fourth column has the percent identified only by elevation; the next column indicates whether this elevation-only ("E-only") area includes former estuarine habitat, as determined by local expertise. The sixth column has the percent identified only by historical mapping; the next column indicates whether this ("H-only") area includes estuarine habitat, as determined by local expertise. The next column indicates whether the elevation (E) or historical mapping (H) estimates of change in estuary extent were considered robust. The penultimate column lists the change in estuary extent in the mapped portion, using whichever estimates were robust. The final column lists the change in tidal marsh extent based on historical mapping. The final rows show the averages or percentages across all estuaries. Darker shading represents higher numbers. Appendix C provides more detail.

Region	National Estuarine Research Reserve associated with estuary	Both Elevation and Historical Map	Elevation only ("E-only")	E-only includes former estuarine habitats	Historical Map only ("H-only")	H-only includes former estuarine habitats	Which change estimates are accurate?	Estuary extent change: best estimate	Tidal marsh extent change from historical analysis
Pacific	Padilla Bay	69	28	X	3	X	E	-50	-84
	South Slough	66	12		22	X	H	-17	
	San Francisco Bay	91	1		8	X	E & H	-65	-63
	Elkhorn Slough	67	15		19	X	E & H	-44	-63
	Tijuana River	51	7		42	X	H	-43	-37
Northeast	Wells	83	10	X	7	X	H	15	-16
	Waquoit Bay	53	44	X	3	X			-15
	Great Bay	88	12	X	1		E	-10	-8
	Narragansett Bay	65	30	X	5	X			
	Connecticut	79	15	X	6	X	E	-14	-10
Mid-Atlantic	Hudson River	67	5		28	X	H	-35	-15
	Jacques Cousteau	92	6	X	2	X	E & H	-2	-12
	Delaware	90	8		2		E & H	-1	-25
	Chesapeake Bay VA	60	37	X	3	X			4
	Chesapeake Bay MD	83	16	X	1				-3
Southeast	North Carolina	68	11	X	21	X	H	-10	-31
	North Inlet-Winyah Bay	74	24	X	2	X	E	-8	48
	ACE Basin	81	14	X	5	X	E	-7	-4
	Sapelo Island	91	7	X	2		E	-4	0
	GTM	82	15	X	3	X	E & H	1	-21
Gulf	Apalachicola	73	12	X	15	X		fairly stable	17
	Rookery Bay	85	11		4	X		fairly stable	increased
	Weeks Bay	23	29		48	X			-3
	Grand Bay	82	10	X	8	X	H	20	-27
	Mission-Aransas	68	14		18	X	H	17	15
Beyond contiguous US	He'eia	55	2	X	43	X	H	-39	-66
	Kachemak Bay	66	34	X	0		E	-5	
	Jobos Bay	75	0		25	X			
Great Lakes	Lake Superior	73	5	X	22	X	NA	NA	NA
	Old Woman Creek	69	11	X	20	X	NA	NA	NA
Average across all estuaries		72	15		13			-15	-18
Percent of estuaries				67%		83%			

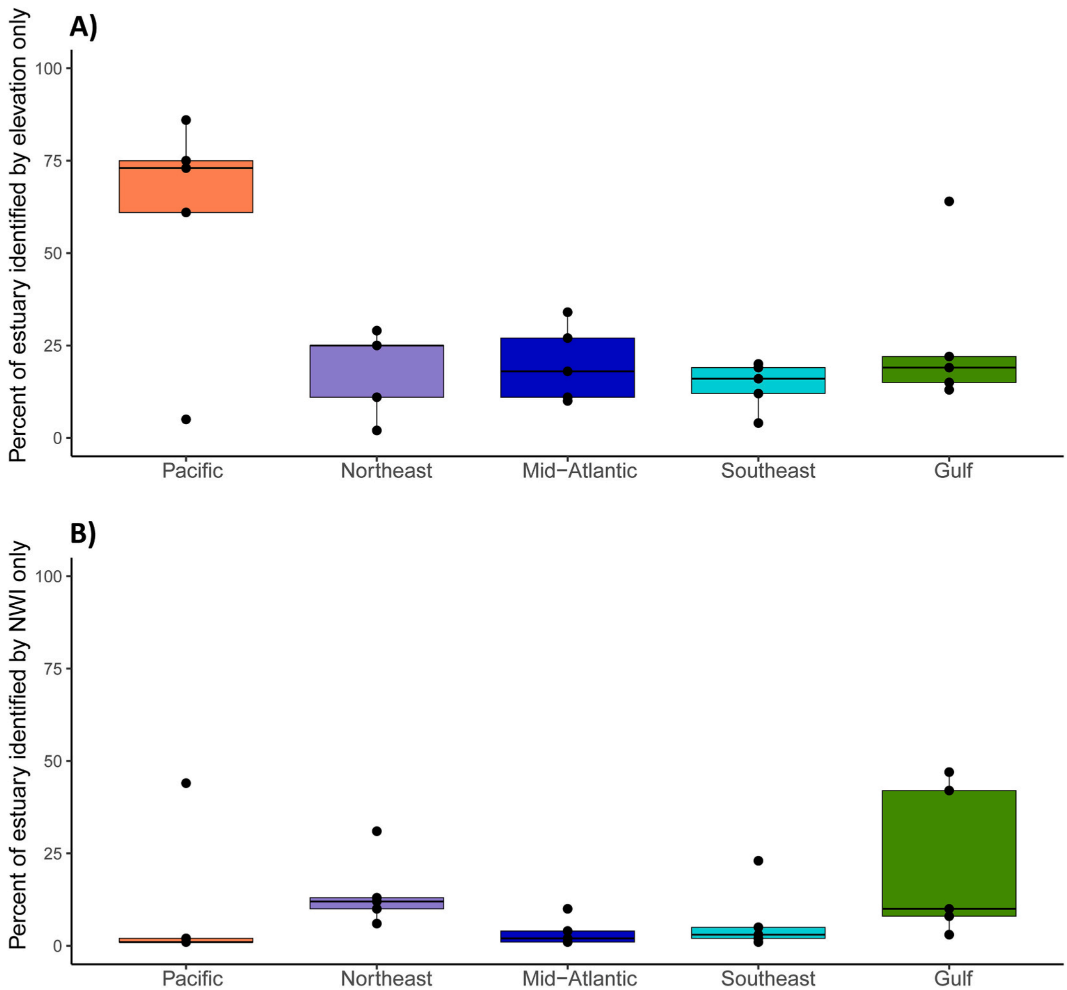

Fig. 2. Estuary mapping by elevation and NWI for 25 tidal estuaries in the contiguous USA.
Each region has five estuaries. A) Percent of joint estuary estimate identified only by elevation; B) Percent identified as estuarine only by NWI. Box plots show median, 25th and 75th percentile, minimum, maximum, and observed data values. Minimum and maximum lines do not include outliers (1.5 times the interquartile range less/greater than the first/third quartile). See Table 2 for numbers for individual estuaries.

At 82 % (23/28) of tidal estuaries, some of the estuarine habitat correctly identified by elevation, but not NWI, included temperate tidal forests. For example, at Apalachicola Bay in Florida where portions of the estuary were last mapped by NWI in 1979, most of the extensive elevation-only areas represent areas known to function as tidal forests, based on local expertise and investigations (Duberstein et al., 2014) (Fig. 4). At many estuaries, Reserve contacts were surprised by the extent of tidal forests; they had previously considered these to be nontidal forested wetlands due to low salinities or riverine settings, even though in many cases there was local tide gauge data indicating daily rise and fall of tides in these areas.

The percentage of the estuary identified only by NWI averaged 13 % across the 28 tidal estuaries, ranging from <1 % at Elkhorn Slough, California to 48 % at Jobos Bay, Puerto Rico (Fig. 3). On average the NWI-only area was greatest in the Northeast and Gulf, but there was high variance within regions (Fig. 2B). At 54 % (15/28) of tidal estuaries, NWI correctly identified some estuarine habitat not included in the elevation-based map, according to local expertise. At 10 of these 15 estuaries, these areas were known to have dense vegetation (such as black needlerush or reed canarygrass) that LIDAR failed to penetrate, generating upwards bias in the LIDAR DEMs and resulting in omission of these areas from the elevation-based map. The Reserve contact at Weeks Bay Reserve in Alabama described this as "vegetation so dense that if you fall, you don't hit the ground." At Apalachicola Bay in Florida, most of the NWI-only areas represent dense vegetation patches that are likely tidal based on a separate analysis (Enwright et al., 2023) (Fig. 4).

At some estuaries, extensive "NWI-only" areas were considered erroneous by local experts. An extreme example was at Tijuana River Reserve in California, where extensive areas mapped as estuarine by NWI are above the reach of tides. Tijuana River is the high outlier on the regional figure; all other Pacific NWI-only areas were very small (Fig. 3). At Hudson River, New York and Kachemak Bay, Alaska, Reserve contacts also suggested various areas mapped as tidal wetlands by NWI are uplands. NWI was particularly unreliable at Kachemak Bay and Jobos Bay, perhaps due to age (last update in 1978 and 1983, respectively).

3.1.2. *Change analyses*

Loss of estuarine habitat was typical at estuaries across the nation; at 89 % (25/28) of tidal estuaries, areas mapped by elevation but not NWI included lost or modified estuarine habitat (Table 2). However, at 75 % (21/28) of tidal estuaries, we were unable to conduct a quantitative change analysis using the approach of Brophy et al. (2019), that is, using elevation to estimate past estuary extent and NWI to estimate current estuary extent. These 21 estuaries included those where NWI failed to identify significant areas of current estuarine habitat (particularly temperate tidal forests in upper estuaries) and thus could not be used as an accurate estimate of present extent, as well as those where elevation missed extensive areas due to dense vegetation preventing the LIDAR signal from reaching the ground.

For the seven tidal estuaries where a robust change analysis could be

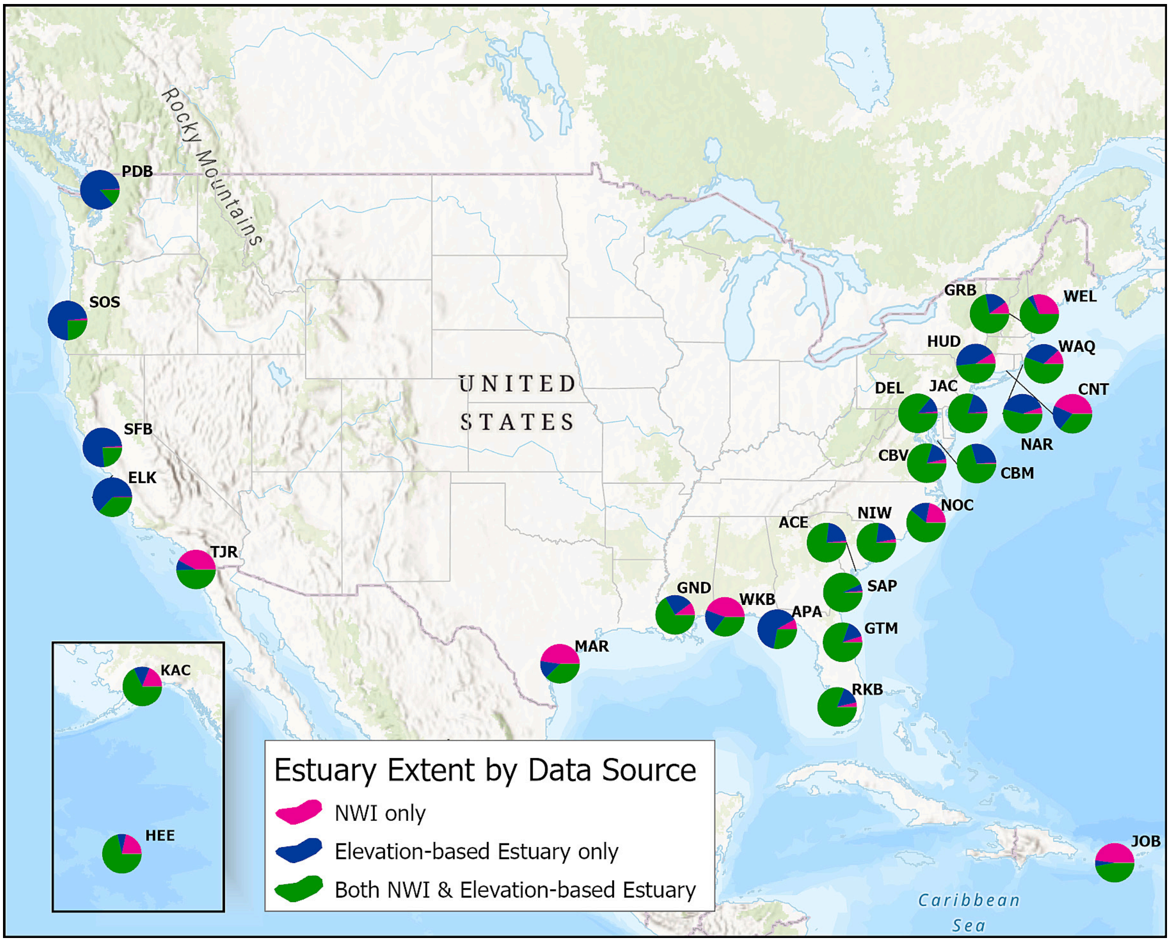

Fig. 3. Regional patterns in percent of joint estuary identified by elevation and NWI.

conducted, estuarine habitat loss was detected with very striking regional differences. For four Pacific estuaries, there was an average of 74 % loss of vegetated habitat (ranging from 61 % at Elkhorn Slough, California to 86 % at Padilla Bay, Washington). Including unvegetated habitat, there was an average of 46 % loss of estuary extent (with range from 29 % at South Slough, Oregon to 72 % at Padilla Bay). In the Pacific region, extensive elevation-only areas mostly represent currently diked areas where estuarine function has been lost; this is most dramatically apparent at Padilla Bay (Fig. 4). At the three estuaries in other regions, rates of loss were much lower: 3–12 % for loss of vegetated tidal habitat, 2–5 % for loss of estuary extent (Appendix C).

3.2. Historical mapping

3.2.1. Mapping diverse past habitat types

The historical maps clearly showed a variety of different habitat types (Fig. 5). Survey notes accompanying many of the T-sheets provided informative descriptions of the surrounding environment and the surveyor interpretations. Most T-sheets appear to have been quite accurate and detailed for subtidal channels, intertidal flats, tidal marsh, some shellfish reefs, grassland and several species of trees (which we grouped as woodland). T-sheets apparently do not consistently map forested wetlands, whether tidal or nontidal. Based on current mapping, it is clear historical maps missed substantial nontidal forested wetlands (for example at North Inlet - Winyah Bay, South Carolina and near GTM Reserve, Florida), and also missed many tidal forested wetlands (for example at Apalachicola, Florida; Weeks Bay, Alabama; Grand Bay, Mississippi; and Chesapeake Bay, Maryland and Virginia). The lake surveys depicted lake, lake shore, river channels and persistent emergent marsh (including wild rice and forested wetland at Lake Superior). The Old Woman Creek map showed extensive human modification (1879) whereas the Lake Superior map showed few human modifications (1861).

Complexity of the historical maps varied widely. Of the 28 T-sheets we analyzed, the largest covered 34,500 ha of surveyed habitat/land use (Mission-Aransas, Texas), while the smallest covered just 1000 ha (Waquoit Bay, Massachusetts). Sapelo Island in Georgia had the highest number of habitat/land use polygons at 3200; Kachemak Bay in Alaska had the fewest, with just 19 polygons. In general the southeast and northeast T-sheets had high densities of polygons, whereas the T-sheets in Alaska, on the Gulf Coast, and in Puerto Rico had low density of polygons.

3.2.2. Changes in habitat distribution and extent

Comparison of the five broad habitat classes in the historical map versus NWI often yielded strong contrasts. Some of these were clear losses due to diking or development; these included tidal wetlands filled and converted to uplands, often for shoreline development such as at the Lake Superior Reserve. Some of these were shifts within estuarine habitat types, such as vegetated tidal habitats becoming unvegetated, or the losses of emergent marsh, wild rice and forested wetland at the Great Lakes Reserves. In some cases, differences between the historical map and NWI did not represent change but instead were artifacts of mapping methods, such as apparent conversion of upland to vegetated tidal wetland in areas that were historically (and are still currently) tidal forests which were not mapped in the T-sheets. For example, at Apalachicola Reserve in Florida, major differences are apparent (Fig. 5). This comparison shows that vegetated tidal wetland (green) has become unvegetated (blue) along the subtidal edge. Much of the apparent conversion of uplands (red) to tidal marsh (green) or to nontidal wetlands (brown) is likely a mapping artifact, because forested wetlands were not consistently distinguished from forested uplands in the historical surveys. Surveyors did note these woodlands were flooded by storm tides, making them tidal forests by today's definitions and raising the possibility that tidal forests were lost as marshes migrated landward.

Because we discovered that both historical maps and NWI often failed to accurately classify tidal forests, we did not universally conduct detailed change analyses using these sources as had originally been planned. However, we did carefully analyze transitions among these habitat types at those estuaries where accuracy of both mapping sources seemed high. Examples from two such estuaries, Elkhorn Slough in California and Great Bay in New Hampshire, illustrate such analyses can be conducted, and how patterns of change can differ among sites (Fig. 6): we detected high rates of loss and transition at the former, low at the latter.

For the 24 tidal estuaries where we analyzed change in tidal marsh extent between the historical maps and NWI, we detected very strong regional differences (Fig. 7A). The Pacific had much less tidal marsh in NWI than in historical maps, indicating high loss of over 60 % on average. Padilla Bay Reserve in Washington had the highest loss (84 %),

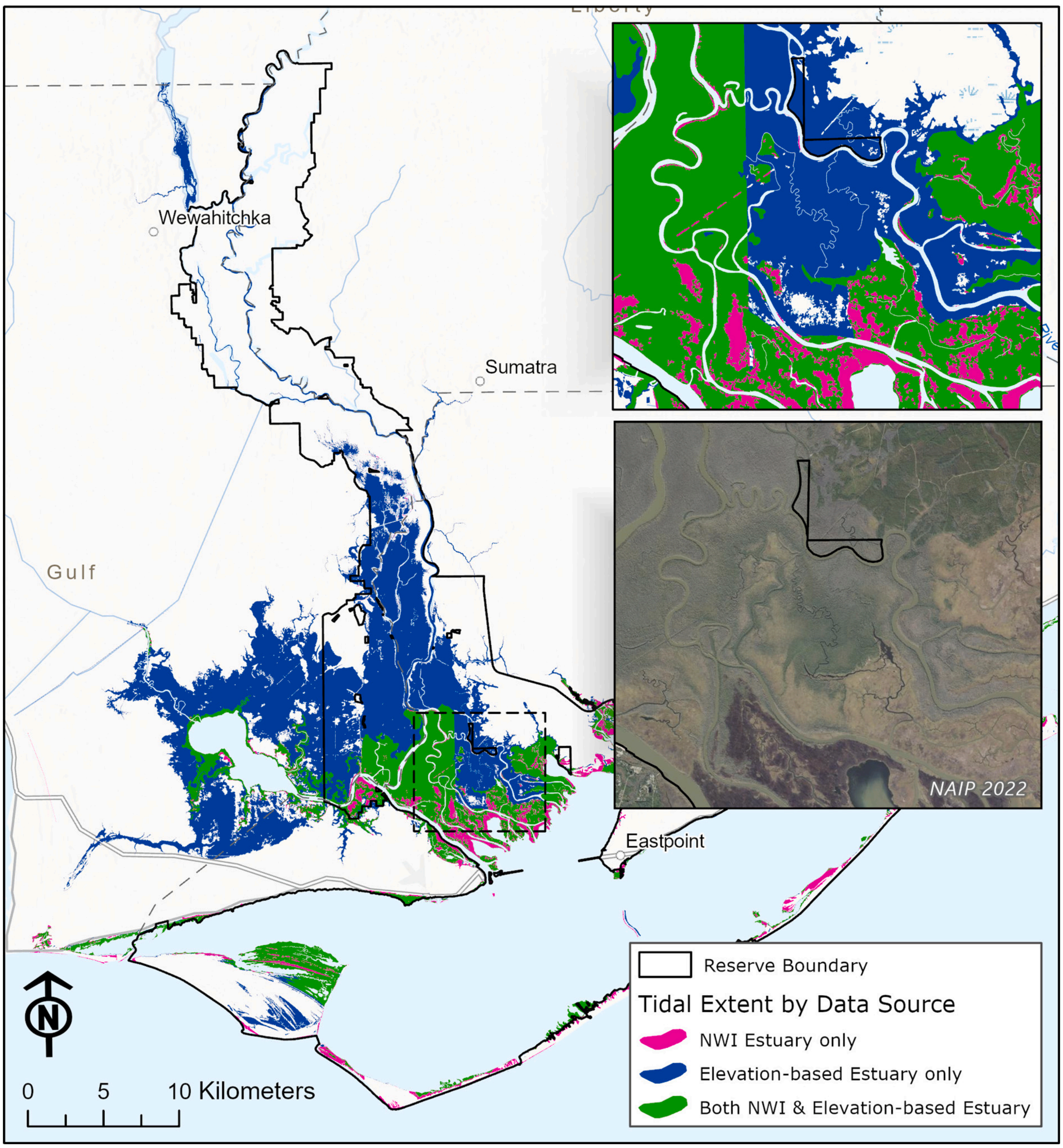

Fig. 4. Elevation-based and NWI estuary extent examples.
Top: Apalachicola Bay, Florida, where most of the northeastern elevation-only areas (blue) represent tidal forests incorrectly identified as nontidal habitat by older NWI mapping (e.g. straight north-south line separates 1979 mapping in blue with 1996 mapping in green), while some of the northwestern areas represent loss; bright pink NWI-only areas are primarily characterized by dense vegetation that led to LIDAR errors
Bottom: Padilla Bay, Washington, where virtually all the elevation-only areas (blue) represent loss to diking and agriculture. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

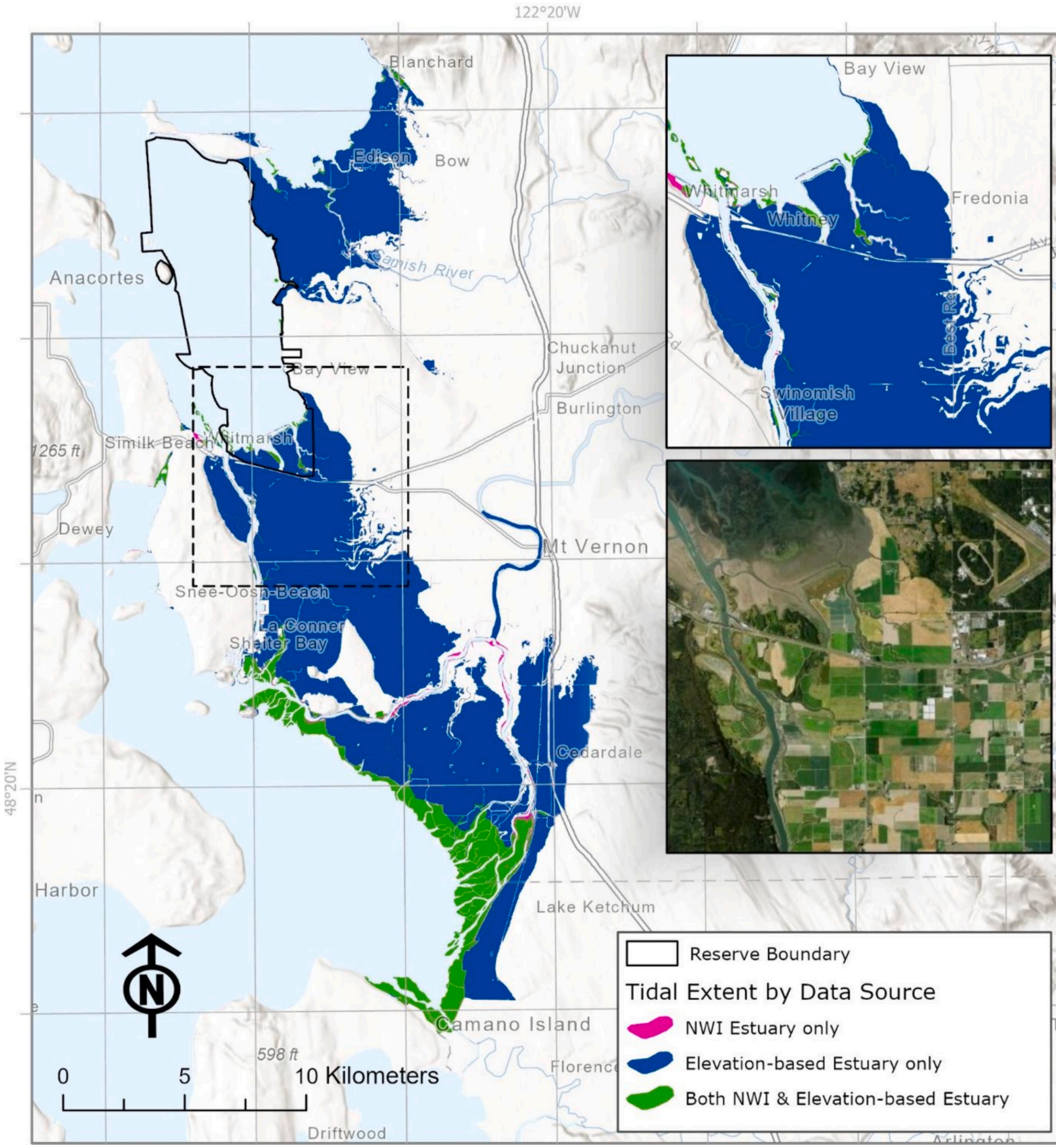

Fig. 4. (*continued*).

due to conversion of tidal marsh to agriculture. Conversely, the Gulf coast generally had more tidal marsh in NWI than in historical maps, indicating some gain. Apalachicola Bay in Florida, for example, had 17 % gain, with tidal marsh replacing forests (likely indicating loss of tidal forests, which were generally not mapped in T-sheets). Other regions had relative stability in tidal marsh extent, though there was variance within regions, especially the Southeast. In many of the estuaries where tidal marsh extent remained similar between past and present, the spatial distribution of marsh changed, with marsh losses (e.g., conversion of marsh to mudflat) balanced by marsh gains (e.g., conversion of forests to marsh).

3.3. *Combining elevation-based mapping and historical mapping*

We compared the two approaches within the relatively small portion of each estuary represented by the historical maps. Within this subarea, the two independent approaches yielded broadly similar maps of past estuaries, with 72 % overlap between estuary extent mapped by elevation versus by the historical map for the 30 estuaries (Table 3). The overlap was highest in the Northeast and lowest in the Pacific (Fig. 8).

On average, 15 % of the estuary in the historical mapping area was identified as estuarine by elevation only (Table 3). At 67 % of the estuaries, local expertise suggested that at least some of these elevation-only areas likely were estuarine in the past. In some cases, the elevation-based map identified past estuarine habitat that was absent

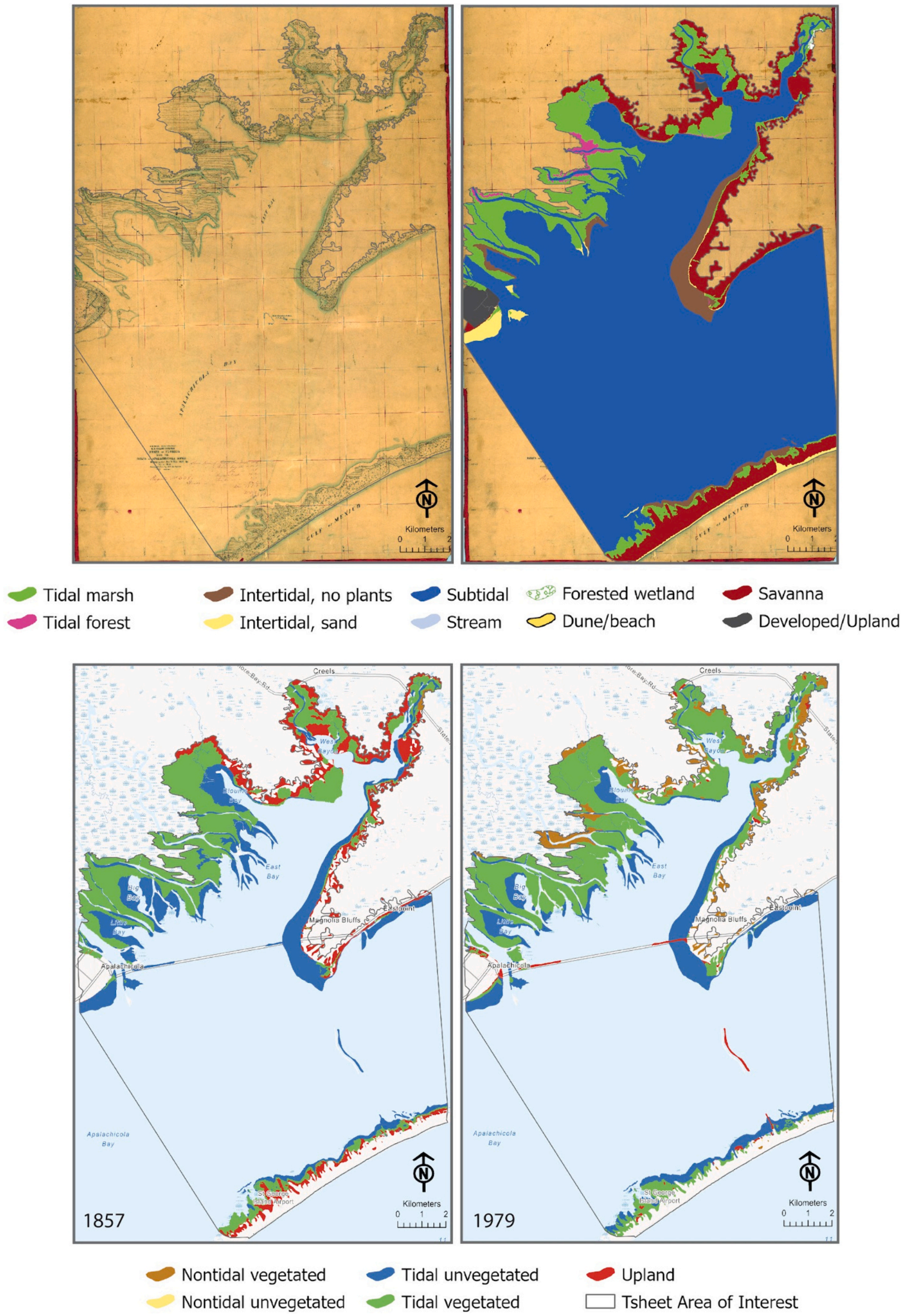

Fig. 5. Example of habitat types on historical map and NWI at Apalachicola Bay, Florida.
Top: Left: T-sheet from 1857; Right: historical habitat classes.
Bottom: Left: grouped habitats as interpreted from historical map (1857); Right: same habitats from NWI (1979) Note: subtidal areas that remained subtidal and upland areas that remained upland are omitted.

from the historical map because the human-induced losses occurred before the historical survey occurred. For instance, marshes had been diked at Padilla Bay Reserve, Washington (Fig. 9), and tidal forests had been converted to rice fields at North Inlet-Winyah Bay, South Carolina, before the T-sheet was drawn. In other cases, tidal forests appear to have been omitted from the T-sheets, but were recognized as likely past estuarine habitat based on elevation. This was the case at various Reserves according to the Reserve contacts, for example at Wells Reserve in Maine (Fig. 9) and Chesapeake Bay Reserve in Virginia.

On average, 13 % of the estuary was identified as estuarine by the historical map, but not by elevation-based mapping (Table 3). At 83 % of the estuaries, local expertise suggested that at least some of these historical-map-only areas were likely estuarine in the past. Almost every estuary had some areas where wetland fill had occurred (as a part of coastal development, or simply due to deposition of dredge spoils or watershed sedimentation); these areas were once estuarine but were not detected by elevation-based mapping because they are currently above the reach of tides (Fig. 9). The most striking example of this was in Tijuana River Reserve in California, where extensive areas of the former estuary are now meters higher than the highest tides, due to sedimentation from the hillsides of the heavily-urbanized city of Tijuana, Mexico. Other areas identified by the historical map but not elevation include habitats where very dense vegetation causes upwards bias in the LIDAR-based digital elevation model, as described above.

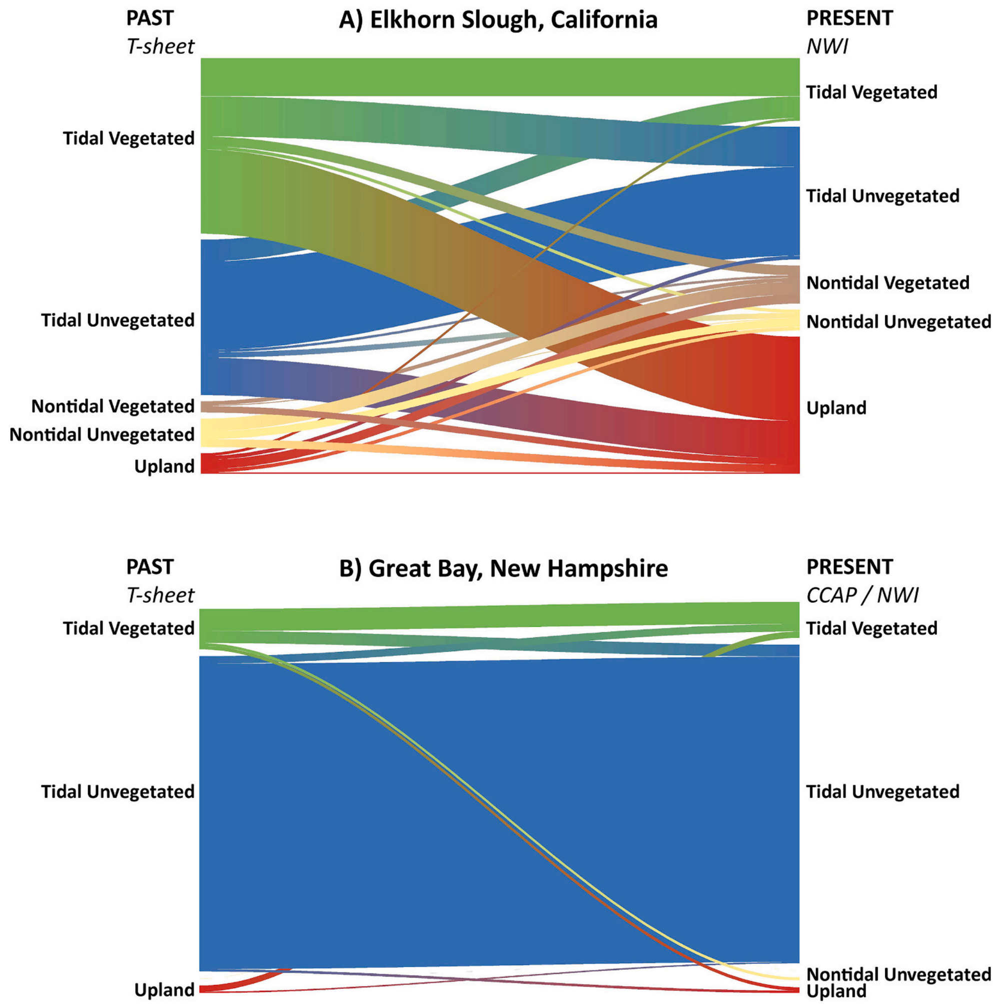

Fig. 6. Transitions among major habitat types.
A) Elkhorn Slough, California: example of estuary with many changes, including much conversion of tidal vegetated to tidal unvegetated and upland habitat. B) Great Bay, New Hampshire: example of estuary with relatively few changes in extent of major habitat classes. Note: subtidal areas that remained subtidal and upland areas that remained upland are omitted.

Within the historical map area, we were able conduct change analyses for the 71 % (21/28) tidal estuaries where at least one estimate of change was considered robust (Table 3). This change analysis yielded pronounced regional differences: by far the greatest losses in estuary extent occurred in the Pacific region, while in the Gulf region there appears to have been some gain in estuary extent (Fig. 7B). The other regions appear to have had fairly stable estuary extent within this historical mapped area.

4. Discussion

Our investigation combined characterization of estuary extent from elevation and from historical maps. Both approaches revealed that estuaries were or are larger than generally recognized. Comparing multiple, complementary mapping methods provides valuable new insights into past, current, and potential future estuary extent. Our workflow (Appendix D) and analysis of US estuaries can thus serve as a model for other regions.

4.1. Past estuaries

Elevation-based mapping provided a fairly robust estimate of past estuary extent, based on high overlap with historical mapping and local expertise. Elevation-based mapping provides various advantages relative to historical mapping. First, it is highly replicable and rapidly applicable across large areas (anywhere with a DEM and water-level data), rather than being limited to locations with historical maps. Elevation-based mapping circumvents the problem of inconsistent historical mapping of wetland boundaries or specific habitat types (e.g. forested tidal wetlands), since all areas within the elevational boundary were likely historical estuarine wetlands (barring major natural or anthropogenic changes in ground-surface or water-level elevations). Elevation-based mapping is more objective, since it does not require interpretation of historical map symbology, which can vary across time, geography, and personnel. Elevation-based mapping can also provide an estimate of baseline conditions prior to human modifications, while the earliest maps sometimes were drawn after substantial changes had occurred. For instance, around Padilla Bay Reserve in Washington, extensive tidal marshes had already been lost to diking when the historical map was drawn in 1886, but these areas were detected by elevation. Likewise, near North-Inlet Winyah Bay Reserve in South Carolina, elevation identifies former tidal wetlands already converted to rice cultivation when the historical map was drawn in 1872. However, elevation-based mapping can miss former estuarine habitat where elevations have increased due to natural forces or human activities (such as sediment deposition in high-energy tidal riverine settings, artificial fill in harbors, or anthropogenic sedimentation at Tijuana River Reserve, California), or where DEMs overestimate ground elevation due to dense

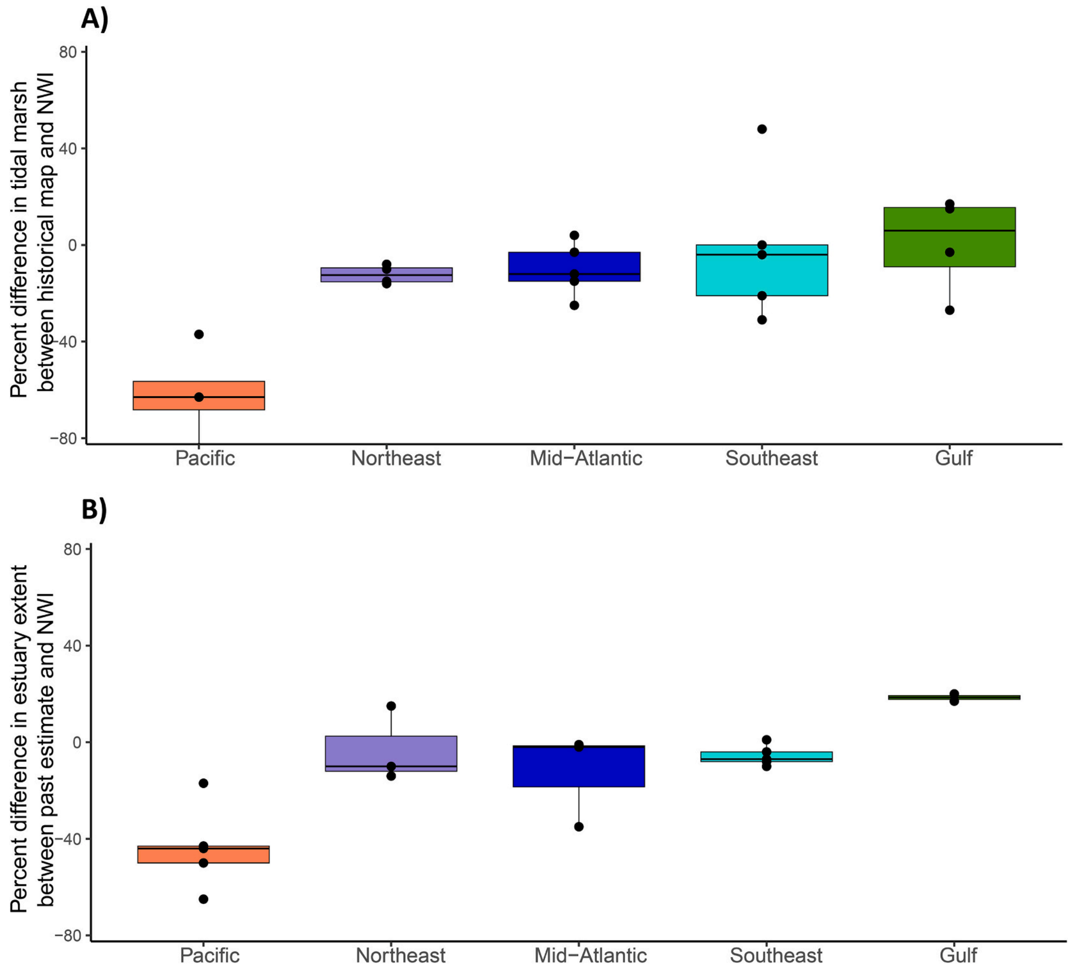

Fig. 7. Change in tidal marsh and estuary extent in tidal estuaries in the contiguous USA.
A) Percent difference in tidal marsh extent between historical map and NWI. B) Percent difference in estuary extent between best past estimate (historical map, elevation-based map, or average of both, depending on which was considered robust, see Table 3) and NWI. Negative numbers represent loss. (See Fig. 2 caption for explanation of box plot elements.)

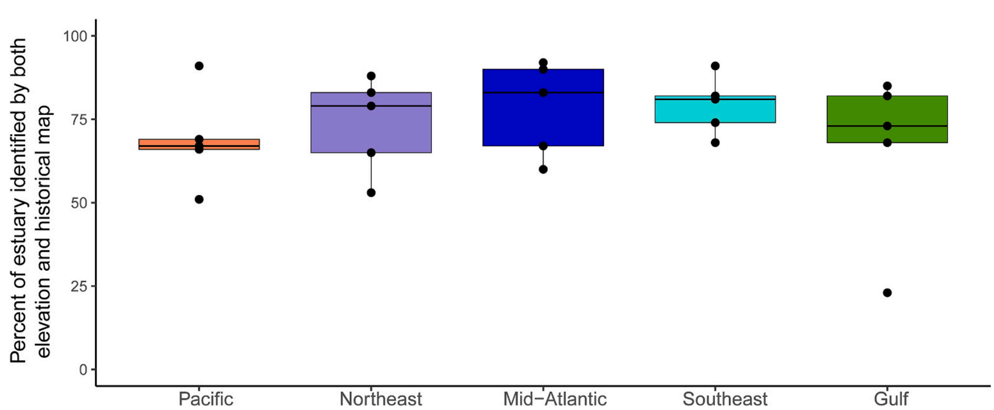

Fig. 8. Overlap between elevation-based and historical map in 25 tidal estuaries in the contiguous USA.
Percent of the joint estuary identified by either method that was identified as estuarine by both elevation-based and historical mapping (that is, the area of overlap between the two methods), within the historical map area. Each region has five estuaries. (See Fig. 2 caption for explanation of box plot elements; see Table 3 for numbers for individual estuaries.)

vegetation interfering with LIDAR. Similarly, elevation-based mapping may overestimate former estuarine habitat where natural forces or human activities have caused a lowering of the ground surface elevation (such as erosion in high-energy tidal riverine settings, or subsidence behind levees and dams).

Historical mapping provided detailed characterizations of past distribution of habitats in and around the 30 Reserves, with some limitations. A major strength of this approach is its reliance on direct observation of habitats at the time of mapping. However, historical maps may cover only a small part of an estuary, and may not be

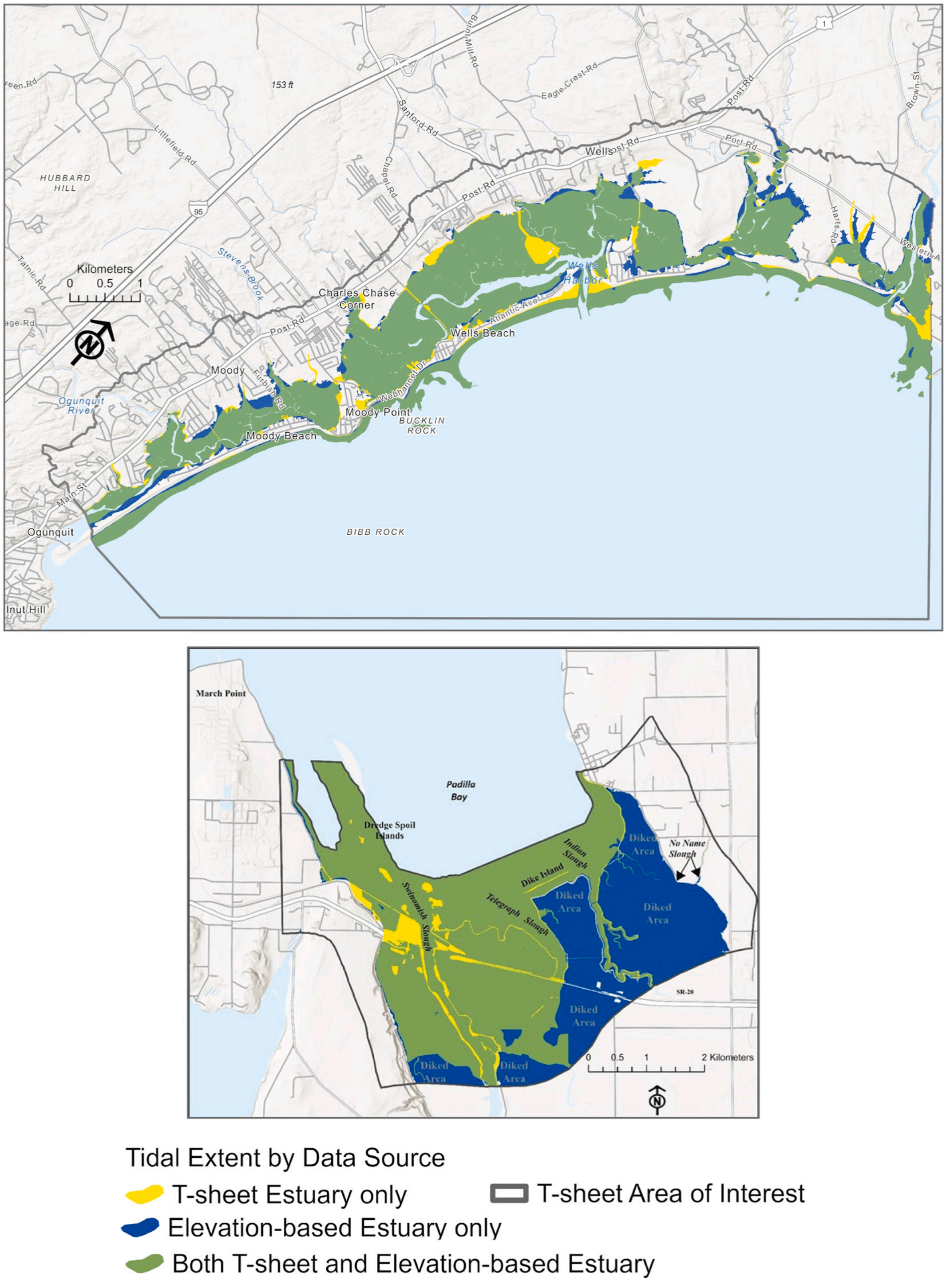

Fig. 9. Example of differences between elevation-based and historical map.
Top: Wells Reserve, Maine. Elevation-only areas (blue) include tidal forests not accurately identified by historical surveyors, and areas altered for agriculture before survey occurred; historical-map-only areas (yellow) consist primarily of areas of wetland fill.
Bottom: Padilla Bay Reserve, Washington. Elevation-only areas (blue) represent areas that were already diked before the historical survey occurred; historical-map-only areas (yellow) represent areas where wetlands were filled. The linear yellow features are dikes, roads, and railroads. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

representative of the overall estuary. Also, they often fail to map forested wetlands, whether tidal or nontidal. Omission of tidal forests from historical maps can result in underestimation of historical estuary extent and habitat losses, and overestimation of tidal forest "gains." Finally, historical maps may not accurately show baseline conditions if major human modifications occurred prior to the mapping.

Given the complementary strengths and differing weaknesses of the two mapping approaches, we recommend combining both approaches to obtain the most robust understanding of estuary extent and estuary change. Each method has some "false negatives," missing some parts of the former estuary; but our study suggests that neither generates extensive "false positives" (areas identified as estuarine that were not).

Therefore, our recommendation is to consider the combined area mapped by either approach as a reasonable "best estimate" of the likely historical estuary extent. Combining these two independent approaches follows best practices for historical ecology – making use of the full suite of relevant resources (McClenachan et al., 2015).

4.2. Present estuaries

Elevation-based mapping is a powerful and logical approach to identifying current estuary extent, because tidal wetlands are defined by tidal inundation, which is determined by the elevation of the land surface relative to the tides. Because tidal inundation shapes plant communities and wetland ecosystem functions, this approach makes sense from ecological and regulatory perspectives too. Elevation-based maps are more consistent and replicable compared to maps of estuary extent based primarily on aerial photo interpretation. Across the 28 tidal estuaries studied, elevation-based mapping revealed a larger estuary than that mapped by interpretation of aerial imagery, enhancing our ability to visualize the true full extent of the estuary. Our work complements other recent efforts combining elevations and tidal datums to map mean high water across the conterminous US, where challenges were encountered on the Gulf coast (Holmquist and Windham-Myers, 2022); and efforts to map tidal marsh on the Gulf coast using a probabilistic approach (Enwright et al., 2023).

Elevation-based mapping greatly improves our ability to map temperate forested and scrub-shrub tidal wetlands. Compared to tidal marsh or mangroves, temperate tidal forests are much harder to detect using aerial photo interpretation because dominant tree species and even understory species are often similar in tidal and nontidal forested wetlands. At >80 % of the estuaries, elevation-based mapping detected tidal forests missed by NWI, and these were often extensive. Upper estuaries (often containing tidal forests and freshwater tidal wetlands) have been understudied compared to lower estuaries, which are often dominated by tidal marsh. Data on hydrology, soils, vegetation, and other wetland characteristics and functions are needed for these upper estuary areas. Such data can further clarify boundaries between tidal wetlands, nontidal wetlands, and uplands (Celik et al., 2021; Doyle et al., 2010). Tidal forests have often been overlooked in planning and restoration efforts, in part because they are so poorly mapped. However, tidal forests provide critical wildlife habitat (Davis et al., 2019; Light et al., 2007), and contribute greatly to carbon storage (Adame et al., 2024; Kauffman et al., 2020; Krauss et al., 2018). Our investigation highlights that temperate tidal forests are common, extensive, poorly mapped across US estuaries, and therefore clearly merit more study and protection.

To accurately assess present estuary extent, we recommend combining elevation-based mapping with maps based primarily on visual assessment of aerial imagery (such as NWI). For mapping US estuaries, NWI is extremely valuable. For identifying emergent (herbaceous) tidal wetlands with very dense vegetation, NWI often performs better than elevation-based mapping that uses LIDAR-based DEMs, because dense vegetation can create an upwards bias in the DEMs (Enwright et al., 2017), though such biases can be corrected to some degree (Buffington et al., 2016). Our work suggests NWI could be made more accurate if complemented with elevation-based mapping, either using NOAA's 50 % exceedance contour as we did, or a new NOAA high tide flooding resource (Sweet et al., 2018). To map the entire estuary, a logical approach is to combine all areas identified as estuarine by either approach, as done for an early study of the Pacific coast (Brophy et al., 2019). Our recommendation is therefore to consider the combined area mapped by either elevation or aerial imagery as a reasonable "best estimate" of the likely current estuary extent. One can have high confidence in areas of overlap identified by both independent methods, and then critically examine the areas identified by just a single method. Elevation-based mapping is better at detecting temperate tidal forests, as described above, and upper reaches of estuaries in general. However, some areas identified by elevation are not currently tidal wetlands (e.g. diked and drained areas); these should be removed from the map of the current estuary, but are important as potential restoration sites. NWI sometimes provides a modifier indicating such status (e.g., diked/impounded), but this modifier is often missing; elevation-based mapping can inform NWI by indicating areas that should have the modifier added, which increases accuracy and value of the NWI mapping and its utility for restoration planning. In mapping these estuaries, we also found that for the Reserves in Alaska and Puerto Rico, NWI maps were nearly 50 years old and highly inaccurate. We therefore recommend investment in improving NWI through regular updates to all US regions, and by incorporating elevation-based mapping into site attribution and identification of wetland boundaries for tidal estuaries.

4.3. Estuarine changes

Habitat change analyses can be very powerful for assessing differences between the past and present. Overall, our nationwide analysis points to net loss of estuarine wetlands, with 15 % loss of estuary extent and 18 % loss of tidal marshes. This analysis of long-term changes reveals more loss than a study examining just two recent decades of tidal wetland change at a global scale using satellite data (Murray et al., 2022), though in both cases, some losses were offset by gains. Our qualitative comparisons of past and present in paired maps for each estuary revealed that estuarine landscapes have been very dynamic over time, with extensive changes in spatial distribution of habitat types even when overall estuary extent did not change substantially.

Our quantitative analyses revealed striking regional differences. Loss of estuary extent and loss of tidal marsh in particular were dramatically greater on the Pacific coast than on other US coasts. An earlier analysis of 55 Pacific estuaries using elevation-based mapping revealed even higher losses: 85 % loss of vegetated tidal wetlands (Brophy et al., 2019). The current study, however, is the first to directly contrast loss among US coastal regions using consistent methodology. Surprises often emerge from examining deeper timelines using historical ecology (McClenachan et al., 2015). Indeed, the Pacific coast has scored high on national evaluations of tidal marsh condition and resilience to sea-level rise (Raposa et al., 2016; Stevens et al., 2023), and may have gained tidal wetlands in past decades, while the Gulf coast has undergone loss (Enwright et al., 2023). These relatively short-term assessments might lead to the conclusion that Pacific estuaries need less investment than other coasts. However, while the remaining tidal marshes may be fairly resilient, investment is clearly needed to restore the very high proportion of Pacific coast tidal marshes and tidal forests that have been lost (Brophy, 2019; Brophy et al., 2019).

We originally intended to conduct quantitative change analyses at all 30 Reserve estuaries, using the elevation-based mapping approach which proved effective at 55 US Pacific coast estuaries (Brophy et al., 2019), as well as the historical mapping approach, which has long been used for change analyses in California and Washington (Grossinger et al., 2011; Stein et al., 2010). However, when we attempted to apply these methods to other US coasts, we encountered a pervasive challenge, namely that our source for present habitat maps, NWI, did not accurately map current estuary extent, particularly for tidal forests. Thus, we could only conduct a more limited set of quantitative change analyses. Future studies using more accurate maps of present conditions could use our elevation-based and historical maps for a more thorough change analysis across these 30 estuaries. However, future analyses using historical maps would still be limited by their frequent omission of tidal and nontidal forested wetlands.

4.4. Future estuaries: using mapping to look forward

The mapping described here has many powerful applications. Below, we illustrate four applications of this mapping: 1) national coastal resilience investment strategies, 2) local strategic planning, 3) climate adaptation planning, and 4) public support for restoration of estuaries.

At a national scale, our study revealed major impacts to estuaries and an unappreciated scale of loss, which should motivate increased investment by the government and non-governmental organizations. Moreover, the strong contrasts among regions highlight that coastal resilience strategies are not "one-size-fits-all," but rather must be tailored to regional needs. We documented vastly greater loss of tidal wetlands on the US Pacific coast compared to other US coasts, indicating the critical need for restoring estuary extent, largely through reconnecting diked and disconnected areas. In other regions, our study revealed pervasive under-recognition and inaccurate mapping of tidal forests. Since tidal forests are already experiencing losses due to climate change (Kirwan and Gedan, 2019), it is vital to better map, protect, and where possible, restore them. Historical ecology studies often challenge status quo management (Beller et al., 2020); similarly, the lessons from our nation-wide mapping should inform future investment strategies in land acquisition, conservation, and restoration.

At a local scale, the maps we generated support strategic planning for estuarine management. We concur that "comprehensive historical analysis of coastal watersheds and wetlands can provide a valuable perspective for regional conservation planning and help spur imagination of alternative future landscapes" (Stein et al., 2010). For example, at Elkhorn Slough Reserve in California, an earlier habitat change analysis (Van Dyke and Wasson, 2005) revealed that half the past estuary has been disconnected by dikes. This motivated an ambitious ecosystem-based strategic planning process (Wasson et al., 2015) and led to a $12 M project to restore formerly diked estuarine habitats and functions (Haskins et al., 2021). At Great Bay Reserve in New Hampshire, our change analysis revealed that the largest potential tidal wetland restoration is located at Great Bay National Wildlife Refuge where a low dam was constructed in the 1940s to convert tidal wetland to fresh and provide waterfowl hunting opportunities. USFWS is currently exploring the feasibility of dam removal. At the Lake Superior Reserve in Wisconsin, historical maps have been used in cultural restoration to identify places where manoomin (wild rice in Ojibwe) used to grow. Manoomin has significant importance ecologically as well as for sustenance, particularly for Ojibwe lifeways.

Local-scale management consists not only of restoring past estuarine habitat, but planning for the future with wise climate adaptation strategies. Historical ecology provides opportunities "to create forward-looking management strategies that are rooted in place and past" (Beller et al., 2020). Understanding the conditions that shaped historical estuaries will be instrumental in identifying the most sustainable locations for tomorrow's estuaries. Areas where the tides have been artificially excluded often provide good opportunities for restoration, especially when holding back the sea becomes infeasible due to sea-level rise. Climate-driven changes in water levels and storm events may lead to new restoration opportunities in overlooked locations identifiable only through historical analyses. Elevation-based mapping also provides an accurate upper estuary boundary that can be moved incrementally upslope with projected sea-level rise, allowing for evaluation of tidal wetland migration opportunities (Stevens et al., 2023). At Tijuana River Reserve in California, historical ecology was used in a scenario planning exercise to inform trajectories of change from the past, to the present, into four possible futures (Goodrich et al., 2018), revealing that if barriers to migration can be minimized, extent of estuary that was lost to sedimentation can be regained as seas rise, albeit in different locations. More broadly, analysis of >100 wetlands in southern California considered past, present, and future together to design regional strategies, yielding optimism for future estuarine habitat scenarios (Stein et al., 2020). At the Lake Superior Reserve, several extreme precipitation events in the last decade resulted in major damage to habitats and millions of dollars in damage to infrastructure (Cooney et al., 2018). The maps generated in this project support enhanced understanding of which areas are at greatest risk of flooding, which is critical in planning for climate change to build more resilient coastal communities.

A final application of estuarine mapping is to build support for conservation and restoration. Historical ecology can counter the insidious problem of shifting baselines (McClenachan et al., 2018). For example, at Elkhorn Slough Reserve, an interactive historical ecology display in the visitor center helps community members recognize that the estuary was once much more vast than it is today, and what now appear to be stagnant agricultural ditches were once vibrant marsh-lined channels. At Tijuana River Reserve, historical maps are used to train teachers on a class exercise that helps students recognize how inlet closure has become more common in the San Diego area over time, due to human land uses. The interactive Story Map we generated (available from https://www.nerra.org/estuary-change/) can be used to educate students or build support from stakeholders as they envision a more resilient future, in and around all 30 of the Reserves. Thus, the combination of mapping approaches used here informs national and local management, supports education about estuary dynamics, and can serve as a model for similar efforts elsewhere in the world.

Ethical approval

This study did not involve human or animal subjects and needed no institutional approval.

CRediT authorship contribution statement

Charlie Endris: Writing – review & editing, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Suzanne Shull:** Writing – review & editing, Visualization, Validation, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrea Woolfolk:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Laura S. Brophy:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Daniel R. Brumbaugh:** Writing – review & editing, Validation, Investigation, Funding acquisition, Conceptualization. **Jeffrey A. Crooks:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Kaitlin L. Reinl:** Writing – review & editing, Validation, Investigation, Conceptualization. **Roger Fuller:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Denise M. Sanger:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Rachel A. Stevens:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Monica Almeida:** Writing – review & editing, Visualization, Validation, Data curation, Conceptualization. **Kerstin Wasson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest related to this work.

Data availability statement

All data and resources generated by this project are available at www.nerra.org/estuary-change; this includes recording of webinars summarizing the project and detailing the methods, as well as all the other resources listed below.

The technical reports that detail the mapping analyses conducted at each of the 30 Reserves are also archived at the National Estuarine Research Reserve's Centralized Data Management Office, and available here: https://cdmo.baruch.sc.edu/science-collaborative/iframe.cfm?project=HiTIDER:%20Estuary%20Change%20Reserve%20Reports.

The historical maps used are available here: https://cdmo.baruch.sc.edu/science-collaborative/iframe.cfm?project=HiTIDER:%20Estuary%

20Change%20Historical%20Maps.

The GIS layers for each of the 30 Reserves are available as file geodatabases here: https://cdmo.baruch.sc.edu/science-collaborative/iframe.cfm?project=HiTIDER:%20Estuary%20Change%20GIS%20Data.

The StoryMap summarizing national synthesis findings, with site examples of each method, examples of how results might be applied, and individual Reserve stories, is available here: https://storymaps.arcgis.com/stories/3cd864fcb3ef478fb6ee3bcd6dfd8ed7.

The Reserve stories featuring each of the 30 sites mapped are also available directly from the Reserve Stories Collection, here: https://storymaps.arcgis.com/collections/6c8ab138d4764351b67779968dcf69c4

To view the nationwide database of layers (including Historical Habitats and Elevation-Based Analysis data) in ArcGIS Online (AGOL) and/or ArcGIS Pro, go to PSMFC AGOL Portal: https://gis.psmfc.org/server/rest/services/HiTIDER/HiTIDER/MapServer

To view the Georeferenced Historical Maps go to PSMFC AGOL Portal: https://gis.psmfc.org/server/rest/services/Hosted/HiTIDER_Tsheets/MapServer

To view the comparison of T-sheet Habitat to NWI in ArcGIS Online (AGOL)and/or ArcGIS Pro go to PSMFC AGOL Portal: https://www.arcgis.com/home/item.html?id=54c87d569ec147799927211e774283e4

All of the above online data are viewable as layers to be toggled on/off or 'swiped' for comparison in the Immersive Data Experience Web App: https://experience.arcgis.com/experience/ef3df91f750d467d9bdad3f9fbd3c54a/page/Homepage/

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110779.

References

Adame, M.F., Kelleway, J., Krauss, K.W., Lovelock, C.E., Adams, J.B., Trevathan-Tackett, S.M., Noe, G., Jeffrey, L., Ronan, M., Zann, M., Carnell, P.E., Iram, N., Maher, D.T., Murdiyarso, D., Sasmito, S., Tran, D.B., Dargusch, P., Kauffman, J.B., Brophy, L., 2024. All tidal wetlands are blue carbon ecosystems. BioScience biae007. https://doi.org/10.1093/biosci/biae007.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecological monographs 81 (2), 169–193. https://doi.org/10.1890/10-1510.1.

Beck, M.W., Heck Jr., K.L., Able, K.W., Childers, D.L., Eggleston, D.B., Gillanders, B.M., Halpern, B., Hays, C.G., Hoshino, K., Minello, T.J., 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: a better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas. Bioscience 51 (8), 633–641.

Beller, E.E., McClenachan, L., Zavaleta, E.S., Larsen, L.G., 2020. Past forward: recommendations from historical ecology for ecosystem management. Global Ecology and Conservation 21, e00836. https://doi.org/10.1016/j.gecco.2019.e00836.

Brophy, L.S., 2019. Comparing historical losses of forested, scrub-shrub, and emergent tidal wetlands on the Oregon coast, USA: A paradigm shift for estuary restoration and conservation. In: Prepared for the Pacific States Marine Fisheries Commission and the Pacific Marine and Estuarine Fish Habitat Partnership. Estuary Technical Group, Institute for Applied Ecology, Corvallis, Oregon, USA.

Brophy, L.S., Greene, C.M., Hare, V.C., Holycross, B., Lanier, A., Heady, W.N., O'Connor, K., Imaki, H., Haddad, T., Dana, R., 2019. Insights into estuary habitat loss in the western United States using a new method for mapping maximum extent of tidal wetlands. PloS One 14 (8), e0218558.

Buffington, K.J., Dugger, B.D., Thorne, K.M., Takekawa, J.Y., 2016. Statistical correction of lidar-derived digital elevation models with multispectral airborne imagery in tidal marshes. Remote Sens. Environ. 186, 616–625. https://doi.org/10.1016/j.rse.2016.09.020.

Celik, S., Anderson, C.J., Kalin, L., Rezaeianzadeh, M., 2021. Long-term salinity, hydrology, and forested wetlands along a tidal freshwater gradient. Estuaries and Coasts 44 (7), 1816–1830. https://doi.org/10.1007/s12237-021-00911-8.

Cooney, E.M., McKinney, P., Sterner, R., Small, G.E., Minor, E.C., 2018. Tale of two storms: impact of extreme rain events on the biogeochemistry of Lake Superior. J. Geophys. Res. Biogeo. 123 (5), 1719–1731. https://doi.org/10.1029/2017JG004216.

Cowardin, L.M., 1979. Classification of Wetlands and Deepwater Habitats of the United States. Fish and Wildlife Service, US Department of the Interior.

Crosby, S.C., Sax, D.F., Palmer, M.E., Booth, H.S., Deegan, L.A., Bertness, M.D., Leslie, H. M., 2016. Salt marsh persistence is threatened by predicted sea-level rise. Estuar. Coast. Shelf Sci. 181, 93–99. https://doi.org/10.1016/j.ecss.2016.08.018.

Davis, M.J., Woo, I., Ellings, C.S., Hodgson, S., Beauchamp, D.A., Nakai, G., De La Cruz, S.E.W., 2019. Freshwater tidal forests and estuarine wetlands may confer early life growth advantages for Delta-reared Chinook salmon. Trans. Am. Fish. Soc. 148 (2), 289–307. https://doi.org/10.1002/tafs.10134.

Doyle, T.W., Krauss, K.W., Conner, W.H., From, A.S., 2010. Predicting the retreat and migration of tidal forests along the northern Gulf of Mexico under sea-level rise. For. Ecol. Manage. 259 (4), 770–777. https://doi.org/10.1016/j.foreco.2009.10.023.

Duberstein, J.A., Conner, W.H., Krauss, K.W., 2014. Woody vegetation communities of tidal freshwater swamps in South Carolina, Georgia and Florida (US) with comparisons to similar systems in the US and South America. J. Veg. Sci. 25 (3), 848–862.

Edgar, G.J., Barrett, N.S., Graddon, D.J., Last, P.R., 2000. The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical and demographic attributes as a case study. Biol. Conserv. 92 (3), 383–397. https://doi.org/10.1016/S0006-3207(99)00111-1.

Endris, C., Shull, S., Woolfolk, A., Brophy, L., Brumbaugh, D., & Wasson, K. (2024). Habitat Mapping Data Portal. *www.nerra.org/estuary-change*.

Enwright, N.M., Wang, L., Borchert, S., Day, R., Feher, L., Osland, M., 2017. The impact of lidar elevation uncertainty on mapping intertidal habitats on barrier islands. Remote Sens. (Basel) 10 (2), 5. https://doi.org/10.3390/rs10010005.

Enwright, N.M., Cheney, W.C., Evans, K.O., Thurman, H.R., Woodrey, M.S., Fournier, A. M.V., Gesch, D.B., Pitchford, J.L., Stoker, J.M., Medeiros, S.C., 2023. Elevation-based probabilistic mapping of irregularly flooded wetlands along the northern Gulf of Mexico coast. Remote Sens. Environ. 287, 113451 https://doi.org/10.1016/j.rse.2023.113451.

Goodrich, K.A., Boudreau, D., Crooks, J.A., Eguiarte, A., Lorda, J., 2018. The role of community capitals in climate change adaptation in a binational setting. In: Addressing Climate Change at the Community Level in the United States. Routledge, pp. 243–258.

Grossinger, R., Stein, E., Cayce, K., Askevold, R., Dark, S., Whipple, A., 2011. Historical Wetlands of the Southern California Coast: An Atlas of US Coast Survey T-Sheets, 1851–1889. San Francisco Estuary Institute.

Haskins, J., Endris, C., Thomsen, A.S., Gerbl, F., Fountain, M.C., Wasson, K., 2021. UAV to inform restoration: a case study from a California tidal marsh. Front. Environ. Sci. 9, 642906 https://doi.org/10.3389/fenvs.2021.642906.

Holmquist, J.R., Windham-Myers, L., 2022. A conterminous USA-scale map of relative tidal marsh elevation. Estuaries and Coasts 45 (6), 1596–1614. https://doi.org/10.1007/s12237-021-01027-9.

Kassambara, A. (2020). Ggpubr: "ggplot2" Based Publication Ready Plots. *Https://CRAN.R-project.org/package=ggpubr* [Computer software].

Kauffman, J.B., Giovanonni, L., Kelly, J., Dunstan, N., Borde, A., Diefenderfer, H., Cornu, C., Janousek, C., Apple, J., Brophy, L., 2020. Total ecosystem carbon stocks at the marine-terrestrial interface: blue carbon of the Pacific northwest coast. United States. Global Change Biology 26 (10), 5679–5692. https://doi.org/10.1111/gcb.15248.

Kennish, M.J., 2023. Anthropogenic Drivers of Estuarine Change. CRC Press, In Climate Change and Estuaries.

Kirwan, M. L., & Gedan, K. B. (2019). Sea-level driven land conversion and the formation of ghost forests. *Nature Climate Change*, *9*(6), Article 6. https://doi.org/10.1038/s41558-019-0488-7.

Krauss, K.W., Noe, G.B., Duberstein, J.A., Conner, W.H., Stagg, C.L., Cormier, N., Jones, M.C., Bernhardt, C.E., Graeme Lockaby, B., From, A.S., Doyle, T.W., Day, R. H., Ensign, S.H., Pierfelice, K.N., Hupp, C.R., Chow, A.T., Whitbeck, J.L., 2018. The role of the upper tidal estuary in wetland blue carbon storage and flux. Global Biogeochem. Cycles 32 (5), 817–839. https://doi.org/10.1029/2018GB005897.

Light, H. M., Darst, M. R., & Mattson, R. A. (2007). Ecological characteristics of tidal freshwater forests along the lower Suwannee river, Florida. In Ecology of Tidal Freshwater Forested Wetlands of the Southeastern United States. W.H. Conner, T.W. Doyle *and* K.W. Krauss *(eds.)* (pp. 291–320).

McClenachan, L., Cooper, A.B., McKenzie, M.G., Drew, J.A., 2015. The importance of surprising results and best practices in historical ecology. BioScience 65 (9), 932–939. https://doi.org/10.1093/biosci/biv100.

McClenachan, L., Matsuura, R., Shah, P., Dissanayake, S.T.M., 2018. Shifted baselines reduce willingness to pay for conservation. *Frontiers in marine*. Science 5. https://www.frontiersin.org/articles/10.3389/fmars.2018.00048.

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., Silliman, B.R., 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. 9 (10), 552–560. https://doi.org/10.1890/110004.

Murray, N.J., Worthington, T.A., Bunting, P., Duce, S., Hagger, V., Lovelock, C.E., Lucas, R., Saunders, M.I., Sheaves, M., Spalding, M., Waltham, N.J., Lyons, M.B., 2022. High-resolution mapping of losses and gains of Earth's tidal wetlands. Science 376 (6594), 744–749. https://doi.org/10.1126/science.abm9583.

Passeri, D.L., Hagen, S.C., Medeiros, S.C., Bilskie, M.V., Alizad, K., Wang, D., 2015. The dynamic effects of sea level rise on low-gradient coastal landscapes: a review. Earth's Future 3 (6), 159–181. https://doi.org/10.1002/2015EF000298.

R_Core_Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/. http://www.R-project.org/.

Raposa, K.B., Wasson, K., Smith, E., Crooks, J.A., Delgado, P., Fernald, S.H., Ferner, M.C., Helms, A., Hice, L.A., Mora, J.W., Puckett, B., Sanger, D., Shull, S., Spurrier, L., Stevens, R., Lerberg, S., 2016. Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices. Biol. Conserv. 204, 263–275. https://doi.org/10.1016/j.biocon.2016.10.015.

Scarborough, C., Welch, Z.S., Wilson, J., Gleason, M.G., Saccomanno, V.R., Halpern, B.S., 2022. The historical ecology of coastal California. Ocean & Coastal Management 230, 106352. https://doi.org/10.1016/j.ocecoaman.2022.106352.

Shalowitz, A., 1962. Analysis and Interpretation of Topographic Surveys. In *Shore and Sea Boundaries, with Special Reference to the Interpretation and Use of Coast and Geodetic Survey Data*, vol. 2. U.S. Government Printing Office, pp. 159–210. https://nauticalcharts.noaa.gov/about/docs/history-of-coast-survey/shore-and-sea-boundaries-volume-two.pdf.

Spencer, S., 2022. ggSankeyGrad: A Ggplot-Based Sankey Graphic with Gradient Flows. Https://github.com/ssp3nc3r/ggSankeyGrad [Computer software].

Stein, E.D., Dark, S., Longcore, T., Grossinger, R., Hall, N., Beland, M., 2010. Historical ecology as a tool for assessing landscape change and informing wetland restoration priorities. Wetlands 30 (3), 589–601. https://doi.org/10.1007/s13157-010-0050-x.

Stein, E.D., Doughty, C.L., Lowe, J., Cooper, M., Sloane, E.B., Bram, D.L., 2020. Establishing targets for regional coastal wetland restoration planning using historical ecology and future scenario analysis: the past, present, future approach. Estuar. Coasts 43 (2), 207–222. https://doi.org/10.1007/s12237-019-00681-4.

Stevens, R.A., Shull, S., Carter, J., Bishop, E., Herold, N., Riley, C.A., Wasson, K., 2023. Marsh migration and beyond: a scalable framework to assess tidal wetland resilience and support strategic management. PloS One 18 (11), e0293177. https://doi.org/10.1371/journal.pone.0293177.

Sweet, W.W.V., Dusek, G., Obeysekera, J., Marra, J.J., 2018. Patterns and projections of high tide flooding along the US coastline using a common impact threshold. NOAA Technical Report NOS CO-OPS 086. Https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf.

Van Dyke, E., Wasson, K., 2005. Historical ecology of a Central California estuary: 150 years of habitat change. Estuaries 28 (2), 173–189.

Waltham, N.J., Alcott, C., Barbeau, M.A., Cebrian, J., Connolly, R.M., Deegan, L.A., Dodds, K., Goodridge Gaines, L.A., Gilby, B.L., Henderson, C.J., McLuckie, C.M., Minello, T.J., Norris, G.S., Ollerhead, J., Pahl, J., Reinhardt, J.F., Rezek, R.J., Simenstad, C.A., Smith, J.A.M., Weinstein, M.P., 2021. Tidal marsh restoration optimism in a changing climate and urbanizing seascape. Estuar. Coasts. https://doi.org/10.1007/s12237-020-00875-1.

Wasson, K., Suarez, B., Akhavan, A., McCarthy, E., Kildow, J., Johnson, K.S., Fountain, M.C., Woolfolk, A., Silberstein, M., Pendleton, L., 2015. Lessons learned from an ecosystem-based management approach to restoration of a California estuary. Mar. Policy 58, 60–70.

Wasson, K., Raposa, K., Almeida, M., Beheshti, K., Crooks, J.A., Deck, A., Dix, N., Garvey, C., Goldstein, J., Johnson, D.S., Lerberg, S., Marcum, P., Peter, C., Puckett, B., Schmitt, J., Smith, E., Laurent, K.St., Swanson, K., Tyrrell, M., Guy, R., 2019. Pattern and scale: evaluating generalities in crab distributions and marsh dynamics from small plots to a national scale. Ecology 100 (10). https://doi.org/10.1002/ecy.2813.

Wolanski, E., Elliott, M., 2015. Estuarine Ecohydrology: An Introduction. Elsevier.