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Mapping methane reduction potential of tidal wetland restoration in the United States

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Coastal wetlands can emit excess methane in cases where they are impounded and artificially freshened by structures that impede tidal exchange. We provide a new assessment of coastal methane reduction opportunities for the contiguous United States by combining multiple publicly available map layers, reassessing greenhouse gas emissions datasets, and applying scenarios informed by geospatial information system and by surveys of coastal managers. Independent accuracy assessment indicates that coastal impoundments are under-mapped at the national level by a factor of one-half. Restorations of freshwater-impounded wetlands to brackish or saline conditions have the greatest potential climate benefit of all mapped conversion opportunities, but were rarer than other potential conversion events. At the national scale we estimate potential emissions reduction for coastal wetlands to be 0.91 Teragrams of carbon dioxide equivalents year^{-1}, a more conservative assessment compared to previous estimates. We provide a map of 1,796 parcels with the potential for tidal re-connection.

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Improved management of carbon sinks in ecosystems has been suggested to hold potential for climate change mitigation[1,2]. Advantages of these strategies include rapid implementation using available technologies, low to moderate cost, and co-benefits associated with improved ecosystem conditions. Although there are uncertainties in the greenhouse gas mitigation potential of any given strategy, it is generally agreed that natural climate solutions (NCS) must play a role in mitigating climate change in addition to grid, heating, and transportation decarbonization[3].

Coastal blue carbon, described herein as intentional management of carbon sinks, emissions, and stocks in salt marsh, mangrove, and seagrass ecosystems, may have the potential for climate change mitigation[4–7]. A key carbon cycle feature of vegetated tidal wetlands is that feedbacks between soil formation and sea-level rise drive ongoing high rates of soil carbon storage regardless of ecosystem age and maturity[8,9], driving the accumulation of soil carbon stocks[10–13].

A further advantage to coastal restorations in saline tidal wetlands is that they typically emit minimal CH_4, due to the dominance of sulfate reduction over methanogenesis in sulfate-rich, anaerobic soils[14]. Therefore the mitigation benefits of carbon sequestration may not be offset by emissions of that potent greenhouse gas[15]. Coastal ecosystems are and will increasingly undergo change in the coming decades due to the accelerating rate of sea-level rise[16,17], thus enhancing the scale of need and opportunity for management interventions with increasing carbon cycle consequences.

A prominent opportunity for greenhouse gas management in tidal wetlands is the restoration of tidal seawater exchange to wetlands inland of dikes, roads, and railroads that have resulted in impoundment[18]. Impounding wetlands can lead to artificial freshening, enhancing the rate of CH_4 emission[19]. Therefore, restoring tidal flow to wetlands is a potential strategy for reducing CH_4 emissions, an avoided emission that is not reversible as stock accumulations are in tidal and upland systems. In the locations where it has been studied, restoration of these types of sites typically results in restored wetlands with a similar salinity to nearby reference sites[20–23].

An increasing number of countries have stated objectives to implement blue carbon as part of their nationally determined contributions under their climate change mitigation plans[24]. The US was the first country to include coastal wetlands within the National Greenhouse Gas Inventory[25] and coastal wetland restoration is being investigated as an approach in several coastal states[26].

A previous estimate of US blue carbon NCS potential[2,18] for the contiguous United States (CONUS) relied on maps and observations of road crossings made for the US northeast, and diked/impoundment wetland data for southeast states, then upscaled to the CONUS. These studies did not explore the potential carbon effects of restoring former wetlands that are drained, nor did they provide maps of potential restoration sites.

In this paper, we use geographic information systems (GIS) to combine multiple publicly available datasets to map features such as coastal impounded wetlands and waters, as well as low-elevation upland habitats, all potentially restorable to tidal wetland. We estimate new emissions factors based on current mapped salinity in impounded wetlands, and likely salinity following restoration. In this paper, we quantify which types of coastal wetland restorations are most likely to result in a net-cooling effect on a 100-year time scale, as well as how much mitigation potential blue carbon NCS have at a CONUS scale. Finally, we map the locations of potential blue carbon projects which are most likely to result in a net-cooling effect.

Results

We present a map created by layering coastal landcover class[27] and tidal elevation[28], simplifying wetland classes by a coarse two-salinity classification scale, estuarine (>5 ppt salinity) and palustrine (0–5 ppt), and simplifying upland categories into agriculture, forest, bare, and developed (Fig. 1A). These were combined with a map of impoundment status[29] (Fig. 1B), which had not previously been independently assessed for accuracy, to determine the initial class. We combined this with a map of reference salinity, salinity spatially interpolated from the nearest non-impounded tidal wetland[27] (Fig. 1C), to determine the potential restored wetland class.

These maps were used in two separate efforts. First, we used them to estimate areas and potential CH_4 reduction of different types of potential restoration types. Second, we downscaled national-scale emissions reductions to the parcel level on protected areas[30] (Fig. 1D–G) in order to determine parcels, states, and land manager types with an outsized potential for CH_4 reduction.

Both this and previous analyses[2,18] largely focused on CH_4 reduction potential. CO_2 removal was not the main focus of this study, even though CH_4 reduction was expressed in CO_2 equivalents in terms of radiant forcing (CO_2e). Where we did include CO_2 removal on drained lands, it had little effect, even marginal, on the total estimates.

Impounded coastal area is underestimated. We estimate 0.53 ± 0.12 million hectares (M ha) of impoundments for the CONUS coastal zone. These features were underestimated by current mapping products[29] by 50% (Fig. 2). The ratio of estimated impoundment area to mapped impoundment area within the National Wetlands Inventory (NWI)[29] was not significantly affected by the strictness of the definition of impoundment ($p = 0.60$), and did not significantly change between 1990 and 2019 ($p = 0.98$).

The underestimate was driven by relatively high exclusion error for impounded wetlands within NWI (Supplemental Information). User's accuracy, the proportion of mapped area correctly classified, for impoundments was $88.4 \pm 3.5\%$. Uncertainty in the ratio of estimated to mapped area is attributable to map area estimates, the scale of the errors, and the size of the independent validation datasets. Reference points occurred within protected areas, but estimated to mapped area ratios were scaled up nationally for top-level estimates of area and emissions reduction potential.

Impounded open water to palustrine restorations had the greatest estimated area in our map with a median estimated area of 199,981 ha and 95% confidence intervals ranging from 158,923 to 244,022 ha (Fig. 3). Impounded palustrine to palustrine conversions had the second-greatest area, followed by impounded open water to estuarine, then impounded palustrine to estuarine (median = 57,133, 95% CI = 45,255–69,780 ha). Areas of potential conversion of drained agriculture and uplands to estuarine conditions were each <50,000 ha. Any given open water could be fresh, brackish, or saline. Palustrine and estuarine wetlands are defined as vegetated.

Emissions factors and scenarios were calculated using a combination of GIS and expert survey. We estimated new zero-inflated emissions factors, which take into account the fractional area of a salinity conversion, the emissions reduction associated with it, and the likelihood that the conversion is net-cooling on a 100-year time scale (Fig. 3). Conversions from impounded palustrine to estuarine conditions had the highest likelihood of having a net-cooling effect (Fig. 3), representing a reduction of
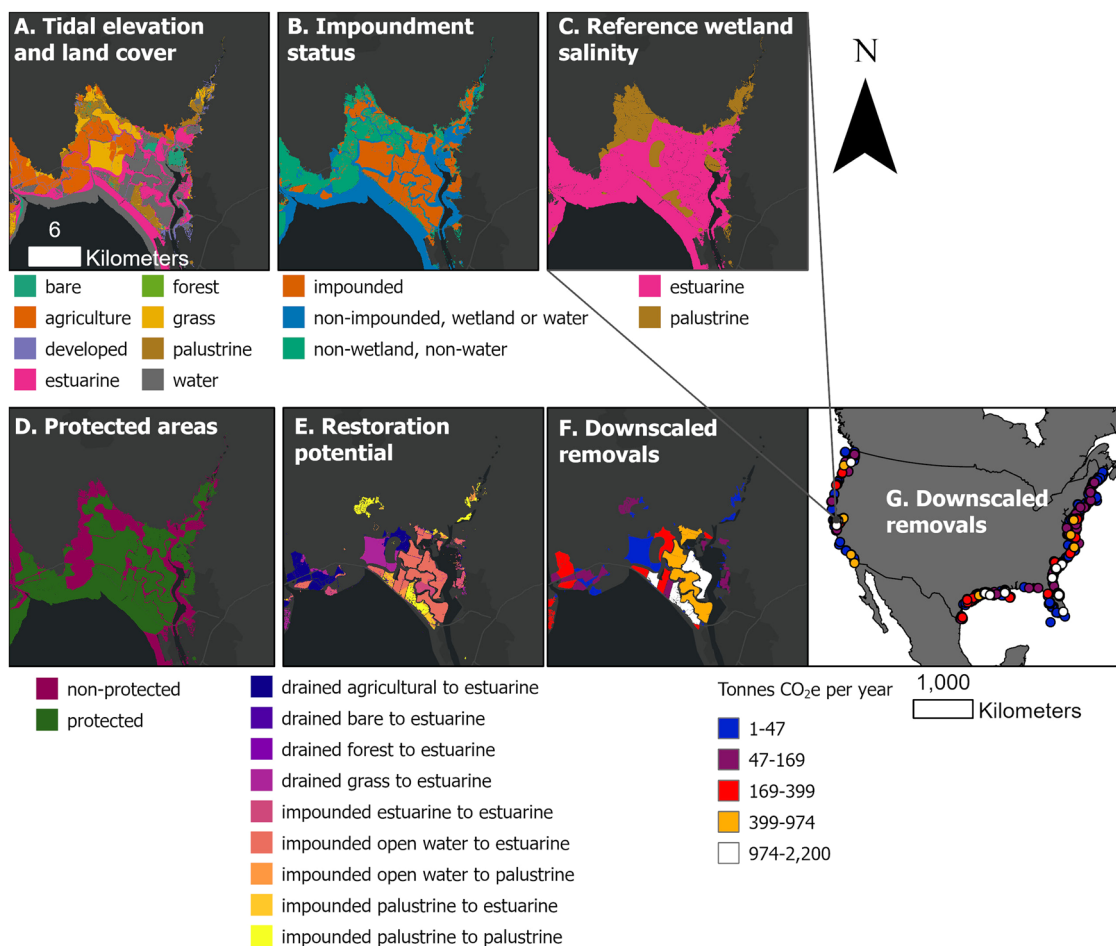
Fig. 1 Geospatial layers were combined to create a downscaled methane emissions reduction potential map. A a combination of coastal landcover class[27] and tidal elevation[28]. **B** impoundment status based on the National Wetlands Inventory[29] **C** reference wetland salinity based on the Coastal Change Analysis Program[27], and **D** protected areas[30]. **E** area estimates of various potential conversions, and **F, G**. a downscaling of methane emissions reduction potential attributable to the parcel level. **A–F** picture the San Pablo Bay National Wildlife Reserve near Vallejo, California, United States. **G** Shows the contiguous United States. Base map credits for **A–F** ESRI Inc. aggregating sources from County of Marin, County of Napa, California State Parks, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, and NPS.[54] Basemap credits for **G**: ESRI Inc.[62].

$1727 \pm$ standard error (s.e.) 561 gCO$_2$e m^{-2} year (y)$^{-1}$. Throughout we use positive numbers to refer to emissions reduction, and negative numbers to refer to emissions.

In cases where the starting and reference salinity classes were the same, or the starting salinity class was unknown because it is defined as open water, we supplemented the GIS analysis with a scenario informed by a survey of coastal impoundment managers using a finer six-step classification (Fig. 4). These emissions factors weight emissions reduction for each possible conversion event by their proportion within the set of survey responses that match the appropriate starting and ending conditions as classified using the palustrine, estuarine, and open water paradigm.

On average, open water conversions to estuarine had the next greatest weighted emissions factor ($203 \pm$ s.e. 80 gCO$_2$e m^{-2} y^{-1}) (Fig. 3). This was followed by conversions of drained agricultural lands and grasslands to estuarine wetlands. Conversions of impoundments resulting in palustrine conditions were less likely to represent a net-cooling scenario than those resulting in estuarine conditions. On average reductions included $46 \pm$ s.e. 50 gCO$_2$e m^{-2} y^{-1}, for impounded palustrine wetlands restored to natural and palustrine conditions, and the same for open water converted to palustrine (Fig. 3). Conversions of drained bare land and forest were less likely to be net-cooling on average when restoration would result in estuarine wetlands. For all drained

upland land classes converted to palustrine wetlands, warming by potential new CH$_4$ emissions outpaced CO$_2$ removal in all Monte Carlo simulations.

We observed general agreement between the GIS analysis and expert survey results when summarizing both using the coarser two-class salinity scale. In both cases, the majority of features were potential impounded palustrine to palustrine conversions (56.5% from GIS and 61.7% from survey), and relatively few were potential impounded palustrine to estuarine conversions (10.5% from GIS and 10.3% from the expert survey) (Supplemental Information).

Impoundments converted to estuarine conditions have the greatest mitigation potential. Our revised estimate of the total emissions reduction potential of reconnecting tidal impoundments is 0.91 Tg CO$_2$e y^{-1} (95% confidence interval [CI], 0.42–1.60 Tg CO$_2$e y^{-1}). Despite the fact that they represented less area, impounded palustrine wetlands converted to estuarine conditions had the greatest net-cooling potential (median = 0.59 Tg CO$_2$e, 95% CI = 0.22–1.04 Tg CO$_2$e; Fig. 3), followed by impounded open water to estuarine (median = 0.11, 0.04–0.23 Tg CO$_2$e; Fig. 3). The total emissions reduction potential of impoundments resulting in palustrine conditions was lower due to their lower emissions factor. The total emissions reduction potential of
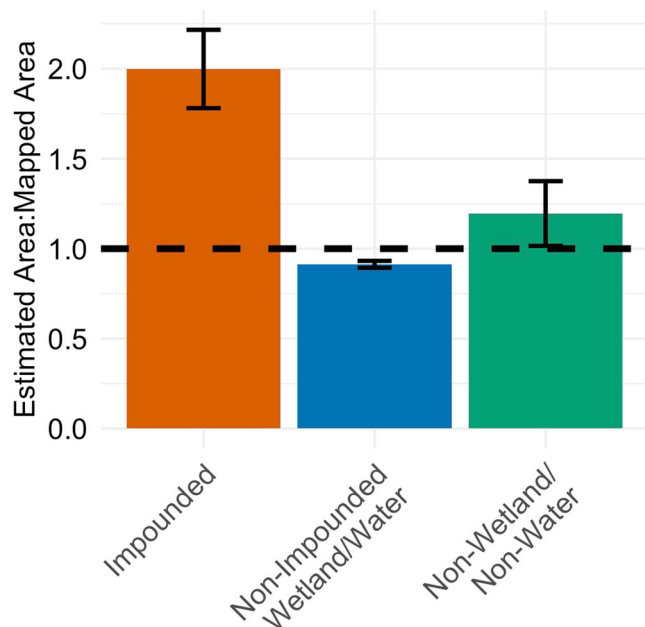
Fig. 2 Estimated to mapped area ratios based on independent accuracy assessment of coastal impoundment status map. (Fig. 1B). Bars represent standard error. The horizontal line represents an ideal one-to-one relationship between the estimated and mapped areas. Bars above the line represent underestimated areas from the mapped source. Bars below the line represent overestimated areas from the mapped source.

impounded estuarine to estuarine conditions was lower still due to their combined lower emissions factor and area (Fig. 3). Including restoration of agricultural and other drained lands to estuarine conditions had a marginal effect on the total estimate of CH_4 emissions reduction potential (Fig. 3).

Additional information on surveyed impoundments. In our expert survey, we found that restoration is planned for 18% of identified impoundments, with this trend largely driven by Pacific Coast restorations where 60% of wetland impoundments surveyed are slated for restoration (Supplemental Information). For Gulf Coast impoundments, 13% are slated to be restored and for the Atlantic Coast, 7% (Supplemental Information). 67% of identified impoundments (as opposed to surface area) were purposeful management choices such as waterfowl management, agriculture, or salt production, whereas 11% were incidental, occurring due to built features such as roads or railroads (Supplemental Information).

Map of wetland parcels. A majority of parcel area with potential for CH_4 reduction is estimated to occur within currently protected areas (54%). We mapped 1796 parcels representing restoration candidates (Fig. 1G)[31], identified as parcels with at least a median probability of 1 metric tonne CO_2e y^{-1} occurring on protected lands[30].

We found that when measured from the side, the median distance between the restoration candidate parcel and the nearest reference wetland was 0 meters, directly adjacent, and 95% bounds of the distribution ranged from 0 to 1945 meters. When measured from the centroid of the parcel, the median distance between the parcel and reference salinity layer was 165 meters, and 95% ranged from 18–2576 meters.
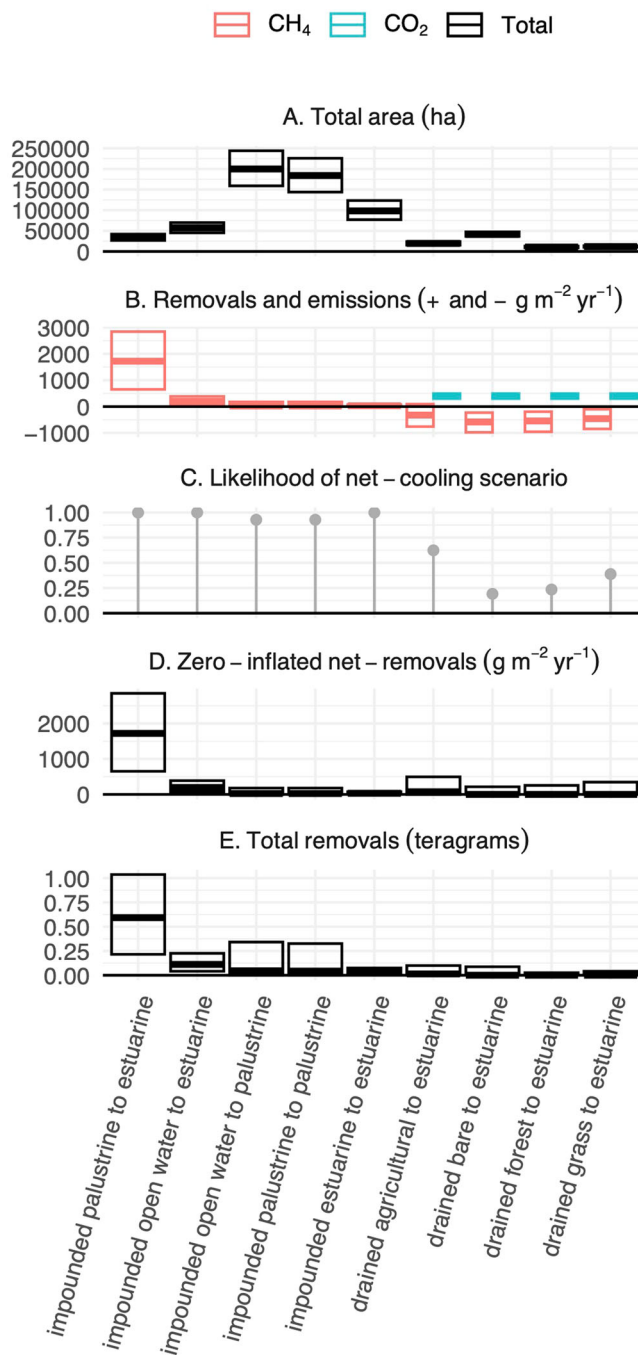

Fig. 3 Workflow shows how we calculated estimated restoration benefits for each restoration type, and propagated uncertainty using Monte Carlo approach. All boxes show median ± 95% confidence interval with the median as the center stripe and box edges as the upper and lower confidence interval. From top to bottom we **A** calculated an unbiased area estimate for each restoration class, **B** used published and new removals and emissions factors to avoid methane emissions, restarted carbon burial, and restarted methane emissions. Removals are positive values and emissions, negative values. **C** We then estimated the probability of a net-cooling scenario. **D** Zero-inflated net-removals scenario so that net-emitting scenarios were omitted, instead treated as zero. **E** multiplied zero-inflated removals by area to estimate total annualized removals.
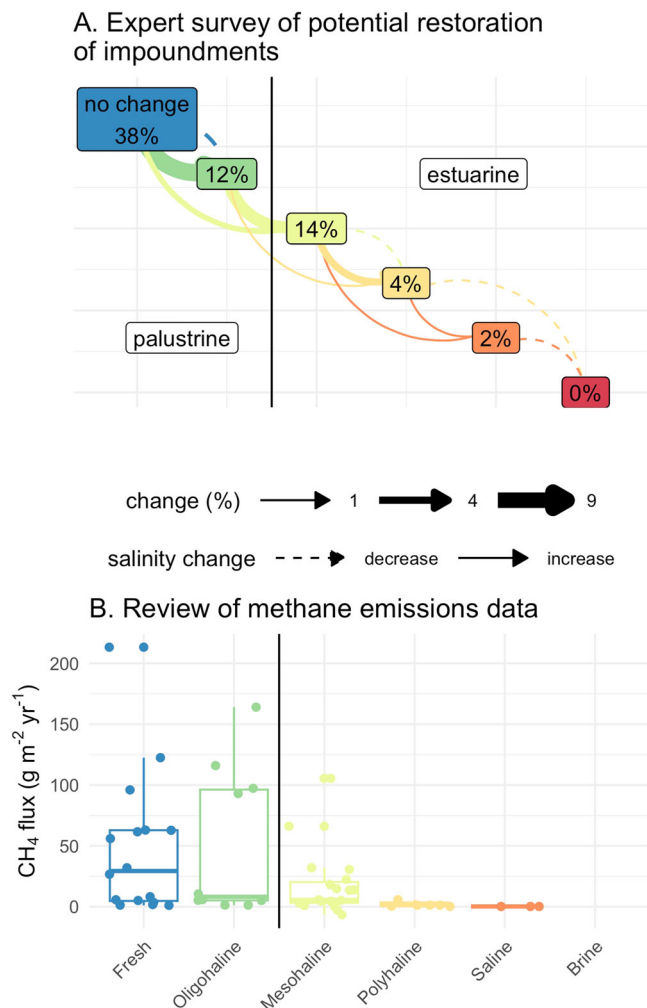
A. Expert survey of potential restoration of impoundments

B. Review of methane emissions data

Fig. 4 Method for tidal restoration potential scenario development.
A Results of a survey with on-the-ground experts showing best estimates for the starting and ending salinity classes of hypothetical restoration of confirmed impoundments. Labels show percentages of the total that would have no salinity changes. Lines show percentages that would change by increasing or decreasing in salinity. **B** Methane emissions (dots) as a function of salinity class. Box and whisker plots highlight the median (center lines), box edges the 1st and 3rd quartile, and whiskers represent either the minimum or maximum value, or 1.5 times the interquartile range, whichever is closest to the median.

States with particularly high concentrations of CH_4 reduction potential include Louisiana (48% of emissions reduction potential), California (26%), and South Carolina (11%) (Fig. 5). Agencies and organizations that manage areas with disproportionately large shares of emissions reduction potential include US Fish and Wildlife Service (45%), various State Fish and Wildlife Services (42%), and State Departments Of Natural Resources (11%) (Fig. 5).

Discussion
There are three major takeaways from this revised assessment of coastal CH_4 emissions reduction potential in the CONUS. First, our total estimate is more conservative than a previous assessment. Second, these estimates could change as more monitoring studies, new accounting frameworks, and new maps become available. Third, potential restoration opportunities are widespread, and many are already planned.

This revised estimate of $0.91 \, Tg \, CO_2e \, y^{-1}$ was lower compared to an earlier assessment by an order of magnitude ($12.0 \, Tg \, CO_2e \, y^{-1}$[2,18]). This change is due primarily to our lower assessment of the area of artificially freshened wetlands, and secondarily due to slightly different emissions factors. In previous studies, the amount of artificially freshened wetland was assumed to be 0.48 M ha[2,18]. We assume a median of 0.057 M ha. Previous studies assume freshened wetlands have an emissions factor of $2400 \, gCO_2e \, m^{-2} \, y^{-1}$ and post-conversion was assumed to be negligible[2,18]. We assume a median palustrine emissions factor post-conversion of $172 \, gCO_2e \, m^{-2} \, y^{-1}$. This, and previous analyses used the same literature review-based dataset[15,32] and sustained global warming potential[2,33], to calculate CH_4 emissions factors.

The difference in emissions reduction potential being attributable to different approaches to estimating areas leads to two important questions. First, which assessment of artificially freshened tidal zone acreage is more accurate? Second, could estimates of acreage and potential emissions reduction be further revised in the future? We think it is plausible that both previous and present studies could be biased, with previous estimates overestimating, and ours underestimating the area available for CH_4-reducing restorations.

Previous studies estimated that 39% of CONUS wetlands were impounded, and 70% of those were classified as artificially freshened[2,18]. The previous studies[2,18] assumed that a relatively large fraction of impounded wetlands were artificially freshened and that in all such cases, salinity would increase to polyhaline if restored. Whether a freshwater impoundment is restorable to brackish or saline conditions depends on the site's position within an estuary and estuary length, which would, in turn, depend on channel depth, freshwater input, and tidal amplitude[34–36].

While we find this explanation for previous studies overestimating area with potential for CH_4-reducing restorations plausible, we also hypothesize that estimates presented herein could underestimate these areas. The GIS-based reference salinity map was based on the Coastal Change Analysis Program (C-CAP), 2006–2010 product[27]. The independent accuracy assessment for this product was not performed using ground data, but other high-resolution mapping sources including the NWI[29,37]. NWI is primarily based on the interpretation of high-resolution remotely sensed images by trained technicians. If C-CAP is overly conservative in detecting salinity over relatively sharp boundaries caused by impoundments, then this issue would not likely be detected using existing accuracy assessment protocols.

The expert survey we performed could plausibly also be biased toward estimating too few artificially freshened impoundments. It could be that responders were overly conservative in assuming no change would occur in salinity if restoration were to occur when they did not have salinity measurements to support their assessments. One piece of evidence for this comes from separating the responses that were based on measurements (49.2%) from those based on expert knowledge (50.8%). Analyzing only the measurement subset increased the amount of potential salinizing restorations slightly from 10.5 to 16.7%, though it also decreased the sample size from 127 to 60.

Further, we hypothesize that by focusing reference points on protected areas but then applying the analysis nationwide, we may have underestimated the area of impounded wetlands. The expert surveys indicate that only 11% of impoundments were incidental, occurring due to built features such as roads or railroads. Kroeger et al.[18], estimated that 74% of impounded areas occurred behind transportation infrastructure. Only 26% were intentionally impounded behind dikes. It could be that impoundments caused by road crossings, or with roads built on older dikes, are more difficult to identify in areal images compared to those impounded by water
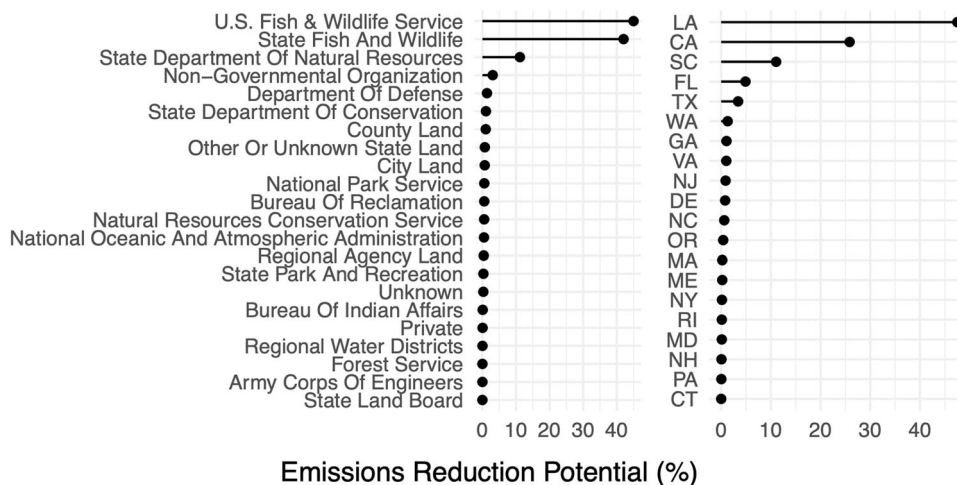
Fig. 5 The percentages of estimated greenhouse gas removal by state and by management entity. The protected areas database[30] was used to categorize relative mitigation potential as a percentage by manager and by state.

control structures. A prominent road crossing-impounded wetland complex slated for restoration on the Herring River in Massachusetts is absent from our map[38] (Supplemental Information). If road-stream-crossings are rarer within protected areas and difficult to detect using NWI's protocols, then we underestimate the prevalence of impoundments nationally due to bias in our reference dataset.

Taken together, new mapping efforts supplementing C-CAP and NWI, based on ground data, collected independently of previous mapping efforts, and encompassing both protected and non-protected areas, could address potential sources of bias in impounded wetland area estimates for this and previous studies.

Additional data and improved accounting guidance could also result in emissions factors being revised in the future. First, emissions factors in this and previous studies were based on a literature review of CH_4 emissions from intact and natural wetlands[15,32]. It is possible that emissions for impounded wetlands and waters could be different due to higher decay rates of soils and/or lower oxygenation of water. Second, guidance on the additionality of carbon deposited in impoundments and reservoirs could revise some assumptions we made. Impounded wetlands[39] and reservoirs[40,41] both bury carbon at rates on the same order of magnitude as intact tidal wetlands, so in this assessment, we decided not to account for any increases in carbon burial associated with restoration. But if future studies were to show that carbon buried in impoundments and/or reservoirs is more allochthonous, being fixed outside of the location where buried, and would likely have been buried in floodplains or the ocean if not trapped behind an impoundment, then CO_2 removal for restorations could be considered additional in future assessments. Additionally, shortening the timeframe over which we calculate global warming potentials (GWP) of CH_4 from 100 years to 30 years (approximately the timeline to meet Paris Climate Agreement goals)[42], could increase the GWP of CH_4 by a factor of at least 2.13. This would both make strategies that avoid CH_4 emissions more potent in our assessments and downgrade those that increase CH_4 emissions while reestablishing carbon burial.

Future studies could benefit from revised emissions factors measuring fluxes in impounded wetlands and open water. High-quality restoration monitoring, before-after, intervention-control studies, are rare in blue carbon monitoring (11%[43]). On the Pacific coast, according to our survey of land managers, a relatively high proportion of impounded wetlands are already slated for restoration (Supplemental Fig. 2). Adding carbon monitoring to planned restorations, even if they are being done nominally for

other purposes, such as habitat restoration, would add to the body of literature and enable more precise assessments of the applicability of blue carbon NCS at a wide scale. Critically, in places where restoration may not alter existing salinity, landward impounded areas are potential wetland migration pathways[44], with the future ecosystem and climate benefits not captured in the current mitigation potential analysis.

Despite the fact that this spatially explicit approach resulted in a more conservative assessment, we conclude that potential blue carbon projects on managed lands are widespread, occurring on all three coasts and in each coastal state. We provide detailed information on the size, projected conversion types, downscaled potential emissions reduction, and associated management entities in our companion data release[31].

The map we present here underestimates the total area of impoundments, but it reliably classifies them when they are mapped. User's accuracy, the complement of commission error, was 88.4 ± 3.5%, exceeding a commonly used threshold of 85%[45]. We found that the total area of impoundments was underestimated by 50%, likely because impoundment status is based on a 'special modifier' within the NWI wetland coding[46] and special modifiers are optional for estuarine and deepwater lacustrine environments[46].

Finally, it is important to provide some context in terms of the importance of the manageable methane emissions examined in this study. The most critical information to convey is that the total, maximum scalability of all approaches for NCS is not of sufficient magnitude to provide meaningful offsets for the ongoing use of fossil fuels. This can be shown based on simple calculations of the magnitude of emissions and natural sinks, without considering non-permanence risks, or changes in the capacity of the land and ocean sinks to absorb carbon dioxide, nor the distinction between biological and geological carbon storage[47]. For instance, in the 2021 Inventory of US Greenhouse Gas Emissions and Sinks, the total emissions of 6,340 Tg CO_2e y[1] are mitigated at a rate of <12% by inventoried sinks[48]. A maximum estimate for full implementation of all known NCS pathways may be equivalent to 21% of the current net of sources and sinks[2]. Carbon management in tidal wetlands, representing a small subset of the total potential for NCS implementation, likewise does not represent an opportunity for a substantial offset of ongoing fossil fuel emissions.

Still, we suggest that the identification and mitigation of these CH_4 emissions have value. They are an anthropogenic emission, as opposed to a biological sink, with no non-permanence risk[18],

and thus are of equivalent value to avoided fossil CH_4 emissions or carbon storage in a long-term geological reservoir. Reducing CH_4 emissions is a policy priority, because of their potential for rapid climate change mitigation and air quality improvement benefit[49,50]. Finally, many approaches to climate change mitigation are needed as none on its own will be of sufficient magnitude to solve the problem of anthropogenic climate change. Instead, many small and large emission sources and sinks will be required. This anthropogenic source is equivalent to >10% of CH_4 emissions from abandoned coal mines in the United States, an emission that is the subject of a >$19 billion effort to mitigate[49].

In this study, we provide new estimates for emissions that could be mitigated by converting coastal impoundments to tidal wetlands. This analysis does represent a more conservative assessment of the potential climate benefit of blue carbon interventions at the national level, but 0.9 Tg CO_2e is still a reduction on the scale of coastal wetland carbon fluxes, representing a little under one-tenth of the annual carbon burial for all coastal wetlands in the US National Greenhouse Gas Inventory (12.2 Tg CO_2e[25]). Note that the anthropogenic CH_4 emissions estimated herein are not currently represented in the US National Greenhouse Gas Inventory. This study found that the highest potential emission reductions per unit area, restoration from palustrine to estuarine conditions, are relatively rare. National assessments of blue carbon NCS could plausibly be revised in the future based on new map products, emissions factor datasets, and accounting guidance. To conclude, NCS is only as valuable as they are feasible, and we provide a map of 1796 parcels in protected areas with potential for net-greenhouse gas-reducing restoration activity.

Methods

To achieve study goals, we built a map of impounded wetlands and waters, as well as landcover types that could be restored to tidal wetland conditions, by layering information from three sources: the NWI[29], the C-CAP[27], and a probabilistic coastal lands map[28]. We performed an independent accuracy assessment of the impoundment maps so that we could estimate unbiased areas. We mapped the prevalence of impoundments and uplands which can potentially be restored to tidal wetlands; then we mapped whether the target salinity of those restorations would be estuarine or palustrine using what we refer to as a reference wetland approach. We estimated manageable emissions and removals by calculating and applying emissions factors to area data for various landcover types, and created a map of individual restoration candidates based on national-scale median likelihood scenarios and uncertainties.

Mapping impoundments

The NWI is unique amongst coastal landcover products in that it maps several wetland sub-conditions such as impoundment status. Other datasets such as C-CAP, do not capture impounded conditions at all. We downloaded NWI maps from all continental US states with tidal wetlands including Washington, Oregon, California, Texas, Louisiana, Mississippi, Alabama, Florida, Georgia, South Carolina, North Carolina, Virginia, Maryland, Delaware, Pennsylvania, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine. Each NWI polygon has a code made up of several capital and lowercase letters as well as numbers indicating various systems, subsystems, wetland classes, subclasses, and special conditions. We iterated through all of the polygons, and classified polygons as tidal using water regime modifiers "L", "M", "N", and "P" for saltwater and "Q", "R", "S", and "V" for freshwater. For impounded wetlands, we classified polygons with codes including the special modifier 'h' as 'diked/impounded'.

To create the impounded wetlands layer, we performed an advanced spatial analysis of the NWI in three steps: first, we wrote an algorithm to decide which wetlands to include, then which lakes and freshwater ponds, then which sections of open water. For wetlands, we included any classified as 'freshwater emergent' or 'freshwater scrub/shrub' if they intersected a shapefile version of the probabilistic coastal lands map. This version of the coastal lands map included any wetland with at least 1% chance of intersecting coastal lands and had single pixels removed. We included any wetlands or water as long as they were classified as intertidal. We also wrote in an exception including features that were classified as 'estuarine deepwater' and impounded, as we observed this type of coding for key features.

Many impoundments were classified as lakes or freshwater ponds. These features do not always intersect the coastal lands product, because they contain open water, which is excluded from the coastal lands layer. To include them we wrote an algorithm to include features based on proximity to mapped tidal features. We included any lakes or freshwater ponds that were within 90 meters of previously mapped wetland features. We let this layer update for 3 iterations to recognize chains of impoundments built in multiple stages.

We included a section of water adjacent to the previously discussed mapped wetland, pond, and lake features. This was because impoundments are sometimes directly adjacent to coastal waters. We extracted features classified as 'estuarine deepwater' and 'rivers', then masked them by a 90-meter buffer around the previously mapped wetland, lakes, and water features of interest.

We additionally used a map of watershed units, at an intermediate level known at hydrologic unit code level-8 (HUC8)[51] to set boundaries on the inland extent. The resulting map classified some areas that were too far inland to be considered tidal, so we manually removed mapped features from watersheds including watersheds inland of the fall line of the Columbia River, and inland in California near Fresno. This three-class impoundment map was used in two further analyses, first for an independent accuracy assessment to estimate the area of impoundments, and second, it was used to generate activities (area) data to estimate total emissions and reductions.

Accuracy assessment for impoundments map

One limitation with relying on the NWI for classification is that there is not a formal accuracy assessment available for the impounded wetlands classification, which is based on an optional set of 'special modifier' codes. An initial investigation based on the site knowledge of the authors and our colleagues indicated potential for errors of inclusion (i.e., natural wetlands or non-wetlands being classified as impoundments) and exclusion (i.e., impoundments being classified as non-impounded wetland or non-wetland)[52,53] (Supplemental Information).

We utilized a stratified random sampling design for our independent accuracy assessment. Two of the map categories, impoundments (5.3%), and non-wetland/non-water (12.2%), made up a smaller percentage than non-impounded wetland or water (82.5%). Overall sample size and stratifications were determined using best practices for classes with low areas (Supplemental Information), and using our best judgment considering person time available. We allocated points as follows: Impoundment = 85, Non-wetland/non-water = 85, and Non-impounded wetland/water = 280. Because we used an unbiased area estimation approach, the sampling design did not have to be proportional to map area[52].

In order to ensure that we could identify on-the-ground experts to provide reliable reference data for each control point, we limited the randomization of reference points to areas of the

map that intersected with the USGS Protected Areas Database[30]. We generated the random points for each category using the 'Create Random Points' tool in ArcGIS Pro[54] and searched the internet and personal networks for contacts associated with each point's management entities. We developed an R Shiny[55] web application to facilitate questions on the status of the control points.

The status of impoundments can be ambiguous; a given area of interest can have varying levels of impoundments, water management that is altered based on time of year or every few years, or a single 30 x 30-meter pixel can contain multiple adjacent landcover classes. Because of this, we treated classifications as "fuzzy sets" as suggested by Woodcock and Gopal (2000)[56], rather than as a binary correct or incorrect (Supplemental Information).

When a point was considered an impounded wetland, we asked for more information about type of impoundment. We also asked if the category that best matched the point had changed between 1990 and 2019. If it had changed, we also asked for more information about what year the changes occurred and what it was before the change occurred.

Of the 450 sample points, we received responses for 445. Nine responses were removed due to low-quality, inconsistent, or incomplete responses. This left us with a total of 436 control points.

Area estimation for impoundments. We created the final blue carbon NCS map by combining three geospatial layers of information: impoundment status derived from NWI, landcover classes (derived from C-CAP), and probabilistic coastal lands map. We classified any C-CAP-mapped wetland or water overlying an NWI-mapped impoundment as impounded (Supplemental Information).

For the impoundment map, the detailed information given by the fuzzy categories, and change/no change status allowed us to run the accuracy assessment statistics on four settings, with a strict and permissive classification of impoundments, to determine if definition strictness affected impoundment area estimates, and at 1990 and 2019, to see if restoration or new impoundment building had a significant effect. For the three-class impoundment status map, we performed a significance test calculating a p-value, one minus the area shared by two normal probability density curves defined by a mean and standard error of impounded area estimates. We calculated p-values for the difference between the 1990 and 2019, strict setting, and for the 2019 strict and permissive setting.

Initial analyses showed no significant effect of time-step nor definition permissiveness on estimated impoundment area so all following analyses involving the impoundment accuracy assessment matrix are reported using 2019, permissive, settings.

Reference-wetland analysis. Because target salinity was found to be crucial to the net-cooling status of restoration according to our reanalysis of emissions factors and salinity, we developed a GIS-based reference-wetland salinity map, meaning that we inferred target salinity, from the salinity of the nearest non-impounded, reference wetland. From our map of potentially restorable wetlands, we extracted pixels that were classified as wetland, had salinity classifications from C-CAP, and were not classified as impounded. We filtered out small parcels (<30 × 30-meter pixel). For impoundments and low-elevation uplands, we assigned a reference wetland salinity by extrapolating the nearest salinity class from adjacent natural wetlands using 'Nearest Neighbor' analysis in ArcGIS pro[54].

Activities data. We classified any C-CAP classes mapped as agricultural land, forest, scrub/shrub, bare or developed open space falling below the mean higher high water spring tide line as

potentially drained wetlands, and lumped them into four categories: agricultural land, forest, grassland, and open space (Supplemental Information).

To estimate area with propagated uncertainty we used Monte Carlo analysis to simulate the underlying accuracy assessment data for impoundment status and C-CAP classification. As Holmquist et al.[57] did, we simulated accuracy assessment matrices by treating them as multinomial distributions and calculated unbiased areas as a function of mapped area and inclusion and exclusion errors. For impoundments, we assumed that the estimated areas of classes for the entire CONUS map were proportional to the subset intersecting the protected areas database, on which the accuracy assessment was conducted. For classes besides estuarine wetlands and open water, we weighted areas by the probability that elevations fell below mean higher high water spring tides from the probabilistic coastal lands map. We did not propagate uncertainty in this step because Holmquist et al.[57] showed that it contributed minimally to national-scale uncertainty in greenhouse gas inventorying.

Scenario development for restored impoundment salinity changes. We conducted a second survey to gain additional information about identified impounded wetland sites. For each impoundment identified in the first survey, we followed up with local experts who had in-person experience with tidal wetland management status in the region or site to ask which of five salinity classes best describes the current annual average salinity inside of the impoundment. The five salinity classes were fresh (0–0.5 parts per thousand [ppt]), oligohaline (0.5–5 ppt), mesohaline (5–18 ppt), polyhaline (18–30), saline (30–50 ppt) and brine (>50 ppt)[58,59]. We also asked what they thought the salinity would be if the hydrology the impoundment blocked were to be fully restored. We also asked how salinity was estimated, how the impoundment blocked tidal exchange, the reason for the impoundment (either incidental or purposeful management decision), approximately when the original impoundment was built, and whether or not there were any plans to restore hydrology.

Duplicate responses for the same point were disregarded if they conflicted. 129 of 145 complete responses were received from experts across the US.

Emissions factors. CH_4 emissions factor data originated from the synthesis performed by Poffenbarger et al.[15], updated for the second state of the carbon cycle (SOCCR-2) report[32]. We calculated mean and standard error for the five salinity classes that were considered under the survey of potential conversion events: fresh (0–0.5 ppt), oligohaline (0.5–5 ppt), mesohaline (5–18 ppt), polyhaline (18–30), saline (30–50 ppt). We also calculated it for the two-salinity subclasses represented in C-CAP: estuarine (>5 ppt) and palustrine (<5 ppt). To propagate uncertainty in the underlying CH_4 emissions data, we fit a skew-normal distribution to annualized CH_4 emissions data, subset by salinity class (Fig. 1). We estimated median and standard error using a bootstrapping approach by taking 1000 random draws from the skew-normal probability distribution with a dataset equal to the size used to calibrate it (Table 1).

We had evidence from the expert surveys that not all coastal impoundments were restorable from fresher to saltier conditions, and when they are, it was usually by one or two steps along a finer five-class salinity scale[58,59] (Fig. 4), so we calculated a 'weighted emissions factor'. The weighted emissions factor is the product of emissions reduction for a salinity class change, and the potential frequency of that conversion event. We calculated weighted emissions factors for each possible salinity conversion type represented by C-CAP which resulted in lower CH_4 emission of

Table 1 Emissions factors used in this study, along with their data sources.

Landcover class	Greenhouse gas	Emission (+) or removals (−) ($gCO_2e\,m^{-2}\,y^{-1}$)	Standard error	
Fresh	CH_4	2259	630	1
Oligohaline	CH_4	2387	805	1
Mesohaline	CH_4	783	290	1
Polyhaline	CH_4	104	39	1
Saline	CH_4	9	0	1
Estuarine	CH_4	587	193	1
Palustrine	CH_4	2318	508	1
All tidal wetland	CO_2	−401	52	2
Drained wetland–agriculture	CH_4	262.1	95.5	3
Drained wetland–forest	CH_4	35.43	12.3	4
Drained wetland–grassland	CH_4	126.3	27.9	5
Drained wetland–bare	CH_4	0	0	6

[1]Data from Poffenbarger et al.[15] updated for the 2nd State of the Carbon Cycle Report[32]. We assumed 45× global warming potential converting CH_4 to CO_2e. Median and standard error bootstrapped from fit of skew-normal distributions.
[2]Data from first US national greenhouse gas inventory[25], analyzed by Holmquist et al.[57]. Presented here as mean and standard error of a log-normal distribution.
[3]Emissions factors originate from Tier I assessments from IPCC wetlands supplement[60]. We assumed 95% cover of non-ditched area, applying emissions factors for "Crop Land, drained, Boreal and Temperate" the Wetlands Supplement Table 2.3[60] and 5% ditched area, applying emissions factors for "Deep drained Grassland/Cropland" ditches from the Wetlands Supplement Table 2.4[60].
[4]Emissions factors originate from Tier I assessments from IPCC wetlands supplement[60]. We assumed 97.5% cover of non-ditched area, applying emissions factors for "Forest Land, drained, Temperate" from the Wetlands Supplement Table 2.3[60] and 2.5% ditched area, applying emissions factors for "Drained Forest Land Drained Wetlands, Boreal/Temperate" ditches from the Wetlands Supplement Table 2.4[60].
[5]Emissions factors originate from Tier I assessments from IPCC wetlands supplement[60]. We assumed 95% cover of non-ditched area, applying emissions factors for "Grassland, drained, nutrient-poor, Temperate" from the Wetlands Supplement Table 2.3[60] and 5% ditched area, applying emissions factors for "Shallow drained Grassland, Boreal/Temperate" ditches from the Wetlands Supplement Table 2.4[60].
[6]We made the assumption that methane emissions are negligible on drained bare land in the intertidal zone.

the restoration. For conversions from estuarine to palustrine conditions, we took the difference between mean palustrine and estuarine emissions (Table 1). We assumed that open-water impoundment CH_4 emissions were equivalent to wetland emissions of the same salinity. For open water to estuarine conversions and estuarine to estuarine, we subset the matrix by wetlands that ended in estuarine class, and began and ended as an estuarine class, respectively.

To propagate uncertainty in the impoundment-weighted emissions factors, we used a Monte Carlo approach, each iteration taking a random draw of the CH_4 mean and standard error. For the salinity changes dataset, we treated the dataset as a matrix of counts with salinity class before on one axis and salinity class after on the other and converted the matrix from counts to proportions. Each iteration, we simulated the salinity conversions survey results by taking a random draw from the multinomial distribution ($n = 129$).

For restarted carbon burial on restored wetlands, we used median value from ^{210}Pb dated soil cores synthesized for the US national greenhouse gas inventory[25,57] (Table 1). For restored impoundments, we only credit reduced CH_4 emissions, because ponds and reservoirs bury allochthonous carbon at rates on par with in situ carbon removal[40]. We assume that US agricultural lands have been drained long enough that they are no longer actively emitting CO_2[18], so they are only credited with potential restarted carbon burial in our analysis.

For CH_4 emissions from drained lands restored to tidal wetlands we referenced Tier 1 emissions factors from the IPCC wetlands supplement[60]. These included agricultural land, grasslands, and forests (Table 1). For bare land, we assumed initial CH_4 emissions were zero.

All CH_4 emissions and emission reductions were converted from $gCH_4\,m^{-2}\,y^{-1}$ to $gCO_2e\,m^{-2}\,y^{-1}$ using a sustained global warming potential of 45×[33].

We determined the probability of whether each conversion event was net-cooling using a second 10,000 iteration Monte Carlo analysis. We sampled all mean and standard errors coming from the impoundment-weighted emissions factor, the carbon burial rates, and the CH_4 emission rates of non-wetland landcover types. In each case, we tallied scenarios in which restored conditions were lower net-emitters of greenhouse gasses than pre-restoration conditions. Proportion of these cases across all Monte Carlo iterations is the probability of a net-cooling scenario.

We also estimated the mean and confidence intervals of each emissions factor using the output of the Monte Carlo iterations. We used a censored distribution, treating negative numbers as zeros, because only positive scenarios count to blue carbon NCS capacity. If the conversion type turns out not to be net-cooling, it would not be considered a viable blue carbon NCS strategy.

We did not track biomass changes associated with potential restoration events. We did not take into account the likelihood of restoration success or political or economic feasibility. For this analysis, we did not consider N_2O emissions due to a lack of data[18].

Total flux estimate. In addition to propagating uncertainty in emissions factors and activities data, we used Monte Carlo analysis to propagate uncertainty in total emissions and removals. Total emissions or removals were estimated as the sum total of the emissions factors ($CO_2e\,area^{-1}\,y^{-1}$) multiplied by their respective activities data (estimated areas), for each potential restoration type. We report the mean, as well as the 95% credible intervals using the output of the Monte Carlo analysis.

Candidate site mapping. To map candidate sites, we converted the raster including current land classification, reference wetland salinity, probability elevation is below mean higher high water spring, protected status, mean emissions reduction potential, and lower and higher 95% confidence interval (CI) for mean emissions reduction, to polygons in ArcGIS Pro[54]. We only included landcover types classified as having a probability of being net-cooling if restored and intersecting the protected areas database. We filtered out small single pixels, with areas <900 m^2. For each polygon, we summarized mean, and CI emission reduction potential. We assumed that spatial autocorrelation in mapping was high at small scales and so treated error as additive rather than as the sum of squares, which we would assume if each pixel's error was completely independent. We filtered out polygons that had net-removals of less than 1 metric tonne (Tonne) per year. We spatially joined parcels with the protected areas database. We report the total median net-removals by State, management type, and management entity according to the protected areas database. Finally, we analyze the distance between candidate restoration parcels, both edges and centroids, and the nearest reference salinity wetland parcel by converting the reference salinity raster to a polygon and using the 'Near' function in ArcGIS pro.

Data availability

online map (https://si.maps.arcgis.com/apps/mapviewer/index.html?webmap=70e7b7281b5e45e6b47c0d49c3bcce29).

Code availability
Code used to collect, and analyze this data, as well as create visualizations are available on FigShare[61].

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