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Coastal wetland management as a contribution to the US National Greenhouse Gas Inventory

Stephen Crooks[1]*, Ariana E. Sutton-Grier[2,3,8], Tiffany G. Troxler[4], Nathaniel Herold[5], Blanca Bernal[6,9], Lisa Schile-Beers[1] and Tom Wirth[7]

The IPCC 2013 Wetlands Supplement provided new guidance for countries on inclusion of wetlands in their National GHG Inventories. The United States has responded by including managed coastal wetlands for the first time in its 2017 GHG Inventory report along with an updated time series in the most recent 2018 submission and plans to update the time series on an annual basis as part of its yearly submission to the United Nations Framework Convention on Climate Change (UNFCCC). The United States followed IPCC Good Practice Guidance when reporting sources and sinks associated with managed coastal wetlands. Here we show that intact vegetated coastal wetlands are a net sink for GHGs. Despite robust regulation that has protected substantial stocks of carbon, the United States continues to lose coastal wetlands to development and the largest loss of wetlands to open water occurs around the Mississippi Delta due mostly to upstream changes in hydrology and sediment delivery, and oil and gas extraction. These processes create GHG emissions. By applying comprehensive Inventory reporting, scientists in the United States have identified opportunities for reducing GHG emissions through restoration of coastal wetlands that also provide many important societal co-benefits.

The IPCC's 2013 Wetlands Supplement provided additional guidance for countries to include wetlands in their national GHG inventories. The United States has responded to this opportunity by including managed coastal wetlands in its 2017 GHG Inventory report and subsequently including wetland data in the 2018 Inventory. The plan is to update the time series on an annual basis as part of the yearly submission of the United States to the UNFCCC. Here we show that it is possible to use publicly available data to incorporate coastal wetlands into national GHG inventories. In the United States, we find that intact vegetated coastal wetlands are a net sink for GHGs. However, despite robust regulation, the United States continues to lose coastal wetlands—the largest loss of wetlands to open water around the Gulf of Mexico is mostly due to upstream changes in hydrology, sediment delivery, and oil and gas extraction. These losses create significant GHG emissions. By applying comprehensive Inventory reporting, the United States has identified important opportunities for reducing GHG emissions through the restoration of coastal wetlands, which also provide many societal co-benefits.

The current GHG Inventory process

One of the lasting major achievements of the UNFCCC was a commitment by all parties under the Convention to regularly assess and report their national GHG emissions and removals. To achieve this, countries follow detailed guidance on GHG compilation, based on internationally agreed[1–3] methodologies, most recently the 2006 IPCC Guidelines for National GHG Inventories (2006 IPCC Guidelines). Methodological guidance covering the agriculture, forestry and other land use (AFOLU) sector represents an important component of GHG reporting. AFOLU is the only Inventory sector in which countries can report GHG emissions and sinks; all other Inventory sectors only report sources of GHGs.

When the 2006 IPCC Guidelines were developed, many wetlands were not included because the science was considered to be insufficient to produce globally applicable default values on GHG emissions and removals due to human activities. The 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands[4] (Wetlands Supplement) helped to fill this gap. Countries currently have an opportunity (not a requirement) to apply the Wetlands Supplement and report GHG emissions and removals that result from wetland land use (for example, forest planting, thinning or harvesting of trees) and land-use change (for example, drainage, rewetting and revegetation), along with other land-use activities (for example, dredging, excavation or aquaculture) and constructed wetlands for wastewater treatment.

The Subsidiary Body for Scientific and Technological Advice under the UNFCCC has asked developed Parties under the Convention to further explore the use of the Wetlands Supplement and invited these Parties to submit information on their experience in the use of the guidance. The United States responded to this request and included GHG emissions and removals from managed coastal wetlands in the 2017 and 2018 National GHG Inventory reports[5,6]. Here we describe some of the main findings of this US experience. The analysis includes all privately owned and publicly owned coastal wetlands (coastal ecosystems with organic and mineral soils that are covered or saturated for part of the year by tidal freshwater, brackish or saline water and are vegetated by vascular plants and may extend seawards to the maximum depth of vascular plant vegetation) along the oceanic shores of the conterminous United States, but at this time the analyses do not include Alaska, Hawaii or US territories. Seagrasses are not currently included

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[1]Silvestrum Climate Associates, San Francisco, CA, USA. [2]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA. [3]National Ocean Service, NOAA, Silver Spring, MD, USA. [4]Sea Level Solutions Center, Institute of Water and Environment, Florida International University, Miami Beach, FL, USA. [5]NOAA Office for Coastal Management, Charleston, SC, USA. [6]Smithsonian Environmental Research Center, Edgewater, MD, USA. [7]US Environmental Protection Agency, Washington, DC, USA. [8]Present address: Maryland/DC Chapter of the Nature Conservancy, Bethesda, MD, USA. [9]Present address: Winrock International, Arlington, VA, USA. *e-mail: steve.crooks@silvestrum.com

Table 1 | Land use on coastal lands of the conterminous United States applied in the Inventory

Land-use category	Total area (in 2011) (ha)
Settlements	151,304
Cropland	267,137
Grassland	65,909
Forest land (dry)	45,401
Palustrine wetlands (F, SS, EM)	1,607,306
Estuarine wetlands (F, SS, EM)	2,188,624
Other Land	NA
Total area	4,325,681

The different land-use types and total area in hectares (in 2011) for the area considered coastal lands in the Inventory. F, forest; SS, scrub shrub; EM, emergent marsh; NA, not applicable.

within the Inventory due to insufficient data on distribution, change through time and carbon stocks or carbon-stock changes as a result of anthropogenic influences.

Quantifying the GHG emissions and removals

The US process of building the Inventory has drawn heavily on freely available Landsat data, country-specific data on soil carbon stocks that have been derived from peer-reviewed literature and IPCC approaches for calculating changes in the carbon stocks. Activity data in the form of land cover and land-use change are derived from a benchmark series of surveys collated under the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). The distribution of organic soils was derived from national soil survey databases.

Quantification of the extent of remaining coastal wetlands, and of former wetlands that are now converted to other land-use categories, is a key element of the analysis. These results were derived from C-CAP (a national LIDAR dataset to provide topography), coupled with analysis of tide station data to map tidal water incursion and the extent of organic and mineral soils from soil survey mapping (SSURGO; https://catalog.data.gov/dataset/soil-survey-geographic-ssurgo-database-for-various-soil-survey-areas-in-the-united-states-). The NOAA's C-CAP produces data and maps using the US Fish and Wildlife's National Wetlands Inventory data to aid in detecting wetlands in satellite imagery. The nature of US coastal lands (excluding open water) is summarized in Table 1. The coastal area that was determined from NOAA C-CAP was established for the first year of GHG Inventory estimation (that is, 1990) and changes to land use were determined as a difference from that 1990 coastal area.

Because of the high density of populations in coastal areas, and consistent with the US managed land definition, the United States determined that all coastal wetlands within the conterminous United States are considered 'managed lands' and as such all estimates of CO_2 emissions and removals, CH_4 emissions and N_2O emissions from aquaculture are included in the Inventory.

In the US Inventory, CO_2 emissions and removals are determined for four primary conversion types: vegetated coastal wetlands that remained vegetated coastal wetlands (VCW–VCW); unvegetated open water coastal wetlands that were converted to vegetated coastal wetlands (UOWCW–VCW); land that was converted to vegetated coastal wetlands (L–VCW) and vegetated coastal wetlands that were converted to unvegetated open water coastal wetlands (VCW–UOWCW).

The conterminous United States hosts 3.8×10^6 ha of intertidal VCW–VCW that consists of estuarine and palustrine emergent marsh, scrub shrub and forested wetlands. A first observation is that approximately 12.3% of the existing coastal wetland area has been converted to other land uses (Table 1). This number would probably be much higher if it were not for the protection provided to wetlands in the United States by legislation including the Clean Water Act. However, even with this legislation, substantial amounts of coastal wetlands are still being lost.

GHGs are estimated for VCW–VCW from gains and losses of carbon stocks and emissions of CH_4. In the latest Inventory (that is, the 2018 submission), only soil CO_2 emissions and removals are reported, with biomass data anticipated to be included in later submissions. Soils are the largest pool of carbon for removal of atmospheric CO_2 by vegetation and long-term transfer into the soil pool in decaying organic matter. Intact VCW–VCW hold a large stock of carbon, estimated to be 870 MtC (3,190 $MtCO_2$-equivalent (CO_2e)) for the top 1 metre of soil. Over the 1990–2016 Inventory period, the US Environmental Protection Agency (EPA) estimated that accumulation occurred at a rate of 12.1–12.2 $MtCO_2e$ per year. Methane emissions from decomposition of organic matter in anaerobic conditions are significant at salinities of less than half that of seawater[7]. Methane emissions of 3.4–3.6 $MtCO_2e\,yr^{-1}$ offset carbon removals from the atmosphere, resulting in an annual net carbon removal rate of 8.5–8.7 $MtCO_2e$. Nitrous oxide emissions, estimated from US aquaculture production, were in the range of 0.14–0.18 $MtCO_2e\,yr^{-1}$ over this period.

Coastal wetland gains and restoration

Both active restoration and engineering activities to rebuild coastal wetlands contribute to increases in coastal wetland area[6]. There are two categories in which these gains can be captured: UOWCW–VCW and L–VCW. Over the 1990–2016 Inventory period, the US EPA estimated that accumulation occurred at a rate of less than 0.005–0.01 $MtCO_2e$ in UOWCW–VCW. Coastal wetland gains, including restoration, can also occur as a result of inundation of unprotected low-lying coastal areas with gradual sea-level rise, flooding of previously drained land behind hydrological barriers and through the active restoration and creation of coastal wetlands by removal of hydrological barriers. These fluxes are captured by the US Inventory in the category L–VCW. The US EPA estimated that accumulation occurred at a rate of 0.01–0.02 $MtCO_2e$ in L–VCW during the reporting period. Methane emissions were reported as 0.01 $MtCO_2e$. The net flux was approximately 0.01 $MtCO_2e$.

Continued wetland loss and emissions

A large release of soil carbon occurs with loss of vegetated coastal wetland through conversion to open water[8]. This conversion is captured in the US Inventory as VCW-UOWCW. Over the 1990–2016 Inventory period, the US EPA estimated an emission rate of 2.1–3.5 $MtCO_2e$ each year. For example, significant loss has occurred in the Mississippi Delta. Although channelization for oil exploration has had a direct impact in the past, present-day losses are largely driven by subsidence that is the result of the changes in river hydrology, sediment supply disruption and oil and gas extraction[9–12]. Soil carbon stocks are also subject to erosion, bringing exposure to oxygen and degradation by benthic organisms[13]. These long-term cumulative effects have also reduced the capacity of the Mississippi Delta to sustain itself above sea level[10,11]. Owing to these and other interacting external drivers that influence the Gulf wetlands, it is challenging to precisely attribute cause and effect of specific drivers, but cumulative net impacts are evident in the change in land cover. This loss of wetlands to open water represents a substantial anthropogenic GHG emission (Table 2).

Of note is the conversion of coastal wetlands to other categories: croplands, grasslands and settlements. Although these are important sources of emissions in the United States, because these estimates are covered under a different reporting category than wetlands, they are not included in the coastal wetland management contribution to the US Inventory. Using C-CAP, it is possible

Table 2 | US coastal wetland loss since 1990, annual net emissions and GHG mitigation potential (1990–2015)

Land-use conversion types	Total area(ha yr^{-1})	Net emission ($MtCO_2e\ yr^{-1}$)	Average net emission[b] ($MtCO_2e\ yr^{-1}$)	Uncertainty (%)	Average GHG mitigation potential ($MtCO_2e$)
Wetland to open water	1,633–9,709	1.26–7.19	3.52	42	62[e]
Wetland drainage[a]	448–1,503	0.03–0.11	0.06	[c]	1[e]
Wetland restoration	2,620–5,316	−(0.003–0.012)	−0.02	[d]	0.01

The total GHG mitigation potential is the CO_2 that could be sequestered if these conversions were reversed to restock or sequester CO_2 compared with the CO_2 sequestered through restoration efforts, based on the average net emissions over this time period. The range in net emission is indicated in brackets. [a]Sum of conversion from wetland to cropland, grassland and settlement over 25 years. [b]Assuming that the upper 1 m of carbon is emitted. [c]The uncertainty for cultivated land and grassland and for settlement is 24% and 42%, respectively. [d]CO_2 and CH_4 uncertainties are 29% and 29%, respectively. [e]If total CO_2 emissions over 25 years were recovered in soil carbon burial through coastal wetland management practices; methane emissions are estimated to contribute 30% reduction in net removal.

to derive the emissions from the change in coastal wetland area to cultivated lands, grasslands and settlements. One striking finding is that although US coastal wetlands are subject to a considerable level of regulatory protection, between 0.3 and 0.11 $MtCO_2e\,yr^{-1}$ of soil carbon is released from piecemeal drainage through conversion to settlements, cultivated lands and grasslands (Table 2). These emissions continue until the soil carbon stock is exhausted or soil water management changes, depending on the soil drainage depth.

Notably, relative to the 25-year range in the annual GHG sink provided by wetland restoration, the GHG mitigation potential that could be provided by changing coastal wetland management practices through reversing drainage or converting open water back to coastal wetland is substantial compared to the mitigation potential achieved with existing rates of wetland restoration based on area; changing management practices could increase US AFOLU sinks by approximately 9% (Table 2; land use, land-use change, and forestry net sink = 716.8 $MtCO_2e$; ref. [6]).

Cascading human impacts

Wetlands are, by their very nature, highly connected systems, sensitive to landscape-scale human activities that can occur off-site, such as upstream water diversions and sediment supply disruption. These characteristics make indirect human impacts to coastal wetlands challenging to include in inventories. For example, the AFOLU sector of inventories includes methodologies to estimate anthropogenic impacts on ecosystems (where and when they occur) that typically are equivalent to the vertical exchange of GHGs between ecosystems and the atmosphere (for example, loss of carbon when a forest is harvested and burned). For wetlands, in which there are interacting human activities operating at multiple scales distributed across the watershed, this makes direct, on-site attribution to a specific management practice difficult. The United States addressed this challenge of applying the Wetland Supplement guidance of an activity-based approach to GHG estimation by recognizing all coastal wetlands as managed and accounting for emissions and removals irrespective of the driver(s). In applying this approach, the United States is perhaps fortunate in that even the large Mississippi river network falls within the national boundary, precluding the challenging considerations of cross-border drivers of coastal wetland loss.

Implications for climate policy and GHG reporting

Some other countries have similar high levels of wetland protection from direct impacts for which the activity-based accounting may fail to adequately capture the GHG impacts of coastal wetland loss. Therefore, one of the main suggestions based on the US data when implementing the Wetlands Supplement is the importance of incorporating a managed land proxy approach (or other IPCC methods that are currently under consideration) into the IPCC Wetlands Supplement guidance in order to more fully capture all the GHG emissions due to anthropogenic effects on coastal wetlands globally. With an update to the 2006 Guidelines planned for 2019, which will set the stage for Inventory reporting for the next decade or more, new approaches, including remote sensing, are being developed and show great promise for application to coastal wetlands[14]. Predictive modelling results for hindcasting in areas and periods with missing data on carbon storage and GHG emissions also show great promise. In addition, modelling can help to enhance our understanding of climate change, sea-level rise and the interactions between natural disturbances and human activities on carbon and GHG dynamics in support of the National GHG Inventory reports[15].

There is a need for guidance for countries on the inclusion of eroding coastal wetlands around the world. The world's rivers have been subject to decreased sediment delivery to coastal waters as a result of upstream dam construction[12]. These human drivers are having a direct impact downstream on wetland integrity. But it can be challenging to partition emissions from these impacts. Although wetland boundaries may or may not follow national boundaries, wetland functions can be affected by landscape changes that are beyond national boundaries. For example, soil carbon production, soil organic matter decomposition and CH_4 emissions could be affected by watershed riverflow and sediment management activities in another country. This includes issues of recognizing the transnational aspect of dam construction and sediment disruption that may result in wetland gain in one country and wetland loss in another. The Mekong Delta is a clear example of this.

In addition to wetland conversion to open water and erosion, another aspect of wetland change—changes in community compositions (or vegetation types) and distributions—also poses a big challenge for assessment and prediction of carbon and GHG Inventory estimations. For example, in the Mississippi River Delta Plain, river diversions, sea-level rise and subsidence interact to affect salinity and flooding regimes, thus leading to changes in vegetation type (including shrinking of brackish marsh while freshwater and intermediate marshes expand[16]) with resulting potential changes in carbon sequestration and GHG emissions.

Broader implications

Notably, although the United States was aided by an established database of land-use change in coastal areas, calculating emissions and removals from coastal wetlands was achieved using data sources that are freely available. Several global land-cover products, including Landsat, are available to all countries. Coupled with IPCC default values or country-specific data, there is no technological barrier to prevent other countries from developing their own estimates of GHG emissions and removals for coastal wetlands. Sharing of experience and capacity building would be important next steps to broaden inclusion.

Additionally, even with wetland protection, regulation and a no-net-loss policy, the United States continues to be a source of GHG emissions associated with past or new drainage of coastal wetlands; without these policies and enforcement mechanisms, emissions would be considerably greater. Restoration of wetlands rebuilds carbon stocks very slowly, but the GHG emissions reductions are greater when restoration is combined with rewetting of drained organic soils, prevention of erosion or with CH_4 reductions by reconnecting impounded wetlands (meaning wetlands that have become fresher because they have been cut off from saltwater inputs due to roads, bridges and culverts, or other human structures). In this latter case, it is possible to reduce emissions by reintroducing salt water so that the freshwater CH_4 emissions decrease[17].

Halting emissions from erosion of the Mississippi Delta is an important opportunity for reducing US emissions from coastal wetlands. Studies suggest that, depending on the sea-level rise scenario, Louisiana is at risk of losing between 211,800 and 467,700 ha of wetlands over next 50 years, emitting between 396 and 916 $MtCO_2$. Restoration actions under the State's Master Plan could reduce these emissions estimates by 35%[18]. This offers considerable reductions in emissions while also maintaining ecological benefits for fisheries, tourism and recreation in coastal economies that are dependent on these activities. Such co-benefits would be accrued in other countries, particularly through soil carbon sequestration gains that come from protection of intact wetland areas.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-018-0345-0.

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Competing interests

The authors declare no competing interests.

Author contributions

S.C. and T.G.T. led the process for including coastal wetlands in the US Greenhouse Gas Inventory with technical input from T.W. and with help from A.E.S.-G., N.H., B.B. and L.S.-B. S.C., A.E.S.-G. and T.G.T. wrote this manuscript with help from T.W.

Additional information

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Methods

Inventory methodology. The US Inventory approach for coastal wetlands applies a general methodology of: (1) defining the coastal land base, recognized as all lands that include wetlands seawards of the highest tides and landward of the extent of the US land representation (which includes all intertidal tidal wetlands and estuarine open water bodies); (2) quantifying land cover within the coastal land area; (3) quantifying annual land-cover change for the 1990–2015 time series; (4) ascribing carbon-stock wetland classes and equations to quantify the emissions and removals that are associated with the land-cover change (using carbon stocks, CO_2 emission or removal factors, or CH_4 or N_2O emission factors, as appropriate); (5) applying stocks and stock change to respective classified land areas; and (6) summing to the respective subcategories of coastal wetlands that remained coastal wetlands and land that was converted to coastal wetlands to determine emissions and removals.

Under the coastal wetlands that remain coastal wetlands category, further subcategorization aligns with the equation and stock or emission factors that are applied to achieve the closest approximation to representing the national circumstances in the Inventory: (1) carbon stock changes and CH_4 emissions on VCW–VCW; (2) carbon changes with conversion of VCW–UOWCW; (3) carbon-stock changes with conversion of UOWCW–VCW; and (4) N_2O emissions from aquaculture.

As specified in the Wetlands Supplement, vegetated coastal wetlands hold carbon in all five carbon pools (that is, aboveground biomass, belowground biomass, dead organic matter (dead wood and litter) and soil organic matter); although typically, soil carbon and—to a lesser extent aboveground and belowground biomass—are the dominant pools, depending on wetland type (that is forests versus marshland). Vegetated coastal wetlands are net accumulators, as soil carbon accumulates in anaerobic soils[4]. Emissions from soil carbon and biomass stocks occur when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands (that is, when managed vegetated coastal wetlands are lost due to subsidence and erosion), but they are still recognized as coastal wetlands in the US Inventory. These carbon emissions result from the conversion to unvegetated open water coastal wetlands, can cause the release of many years of accumulated soil carbon. Conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands initiates the rebuilding of carbon stocks within soils and biomass. In the application of Wetlands Supplement 2 methodologies for CH_4 emissions, coastal wetlands with salinity conditions less than half that of seawater are sources of CH_4, which result from the slow decomposition of organic matter under freshwater, anaerobic conditions[7]. Conversion of vegetated coastal (saline) wetlands to or from unvegetated open water coastal (saline) wetlands do not result in a change in the salinity condition[17] and are assumed to have no effect on CH_4. The Wetlands Supplement guidance provides methodologies and tier 1 default values to estimate nitrous oxide emissions on coastal wetlands that occur because of aquaculture. Although N_2O emissions can occur because of anthropogenic nitrogen loading from the watershed and atmospheric deposition, these emissions are recognized elsewhere in the Inventory and are not reported under Coastal Wetlands. The N_2O emissions from aquaculture result from the nitrogen that is derived from the consumption of the applied food stock, which is then excreted as a nitrogen load available for conversion to N_2O.

Coastal wetland definition and national extent. Boundaries to the extent of managed coastal wetlands were set based on the IPCC definitions of coastal land and coastal wetlands: "Coastal land is land at or near the coast. It is good practice for a country to define the concept of 'coastal land' and its sea- and landward limits in accordance with national circumstances, and to apply the definition consistently across the entire national land area and over time. All land that is not coastal is inland. A coastal wetland is wetland at or near the coast that is influenced by brackish or saline waters and/or astronomical tides. Coastal wetlands may occur on both organic and mineral soils. Brackish and saline water is water that normally contains more than 0.5 or more parts per thousand (ppt) of dissolved salts." In the US Inventory, the landward extent of coastal land is defined by the extent of the mean high-water spring-tide elevation and includes all lands (wetlands and other land uses) at or below this elevation seawards to the seaward extent of the US Land Representation (a boundary that includes all vegetated intertidal wetlands and areas of estuarine open water).

This analysis applies the 2010 C-CAP dataset from the NOAA (https://coast.noaa.gov/digitalcoast/tools/lca). The C-CAP data provide nationally standardized wall-to-wall land-cover and land-change data for the coastal region of the conterminous United States and Hawaii. The data were obtained from Landsat-derived 30-m resolution products. C-CAP land-cover data are available for the years 1996, 2001, 2006 and 2010, with a 2015 update in production.

To approximate the coastal areas that are most likely to be influenced by tidal fluxes along the US coasts, we established a mean higher high-water spring (MHHWS) surface. This area was determined by extrapolating the values of those tides that accounted for 95% (2 s.d.) of all values that exceeded the MHHW over the last three full years. This elevation was calculated for multiple tide gauges along the coasts of the Atlantic Ocean, Pacific Ocean and the Gulf of Mexico. Individual tide gauge values were then used to interpolate a spatially variable surface, using an inverse distance weighted method, which was then added to a previously created MHHW surface. The MHHW surface was created using the best available LIDAR-based elevation data that could be compiled within each coastal area.

In areas that did not have LIDAR-based elevation data to support the establishment of the MHHW surface, estuarine wetland categories (estuarine forested, estuarine scrub shrub and estuarine emergent), unconsolidated shore and coastal open water areas from C-CAP were used to supplement the coastal boundary extent. Lands and waters outside the area that fell between the MHHWS and seaward extent of the land representation were defined as non-coastal. This maximum possible coastal area was then used to extract C-CAP land-cover and land-change data. Only those categories identified as being vegetated wetlands, following the coastal wetland definition, were included. These categories included: palustrine scrub shrub wetlands, palustrine emergent wetlands, estuarine forested wetlands, estuarine scrub shrub wetlands, estuarine emergent wetlands and open water.

Area of wetland type by year and changes associated with these wetlands were compiled for the years between 1996 and 2010, which represent the dates available through C-CAP. Change before 1996 and after 2010 were estimated using the average changes seen over the 14-year C-CAP time series. Conversions from one wetland type to another, including open water, were compiled by year from 1990 to 2015.

GHG estimation methodologies. *Soil carbon stock changes.* Tier 2, country-specific reference soil carbon stocks and carbon accumulation rates stratified by mineral and organic soils, vegetation (based on NOAA C-CAP classes) and climate zone were derived from review of published literature (Supplementary Table 1).

Tier 2, estimates of soil carbon removal associated with annual soil carbon accumulation from managed VCW–VCW (for wetland that remained and open water regions that were converted to wetland) and L–VCW were developed with country-specific soil carbon removal factors multiplied by activity data of the respective land areas. Soil carbon removals were calculated for all intact vegetated wetlands and assumed to be zero for unvegetated bare grounds and open water, following IPCC guidance. For restoring wetlands, carbon removals were recognized with the transition from other lands to vegetated coastal wetlands.

Estimates of emissions with conversion of vegetated wetlands to open water applied a combination of tier 2 level mapping, tier 2 reference soil carbon stocks and tier 1 assumptions about depth of the affected soils. The tier 1 methodological guidance from the Wetland Supplement for estimating emissions following the methodology for excavation when VCW–UOWCW, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with the first order estimates of wetland carbon loss provided in the literature[4,18,19]. A tier 1 assumption is also adopted that all mobilized carbon is immediately returned to the atmosphere (as assumed for terrestrial land-use categories), rather than redeposited in an alternate long-term carbon storage.

Soil methane emissions. Tier 1 estimates of CH_4 emissions for VCW–VCW are derived from the same wetland area used in the analysis of wetland soil carbon fluxes, in combination with default CH_4 emission factors[4] (Supplementary Table 4.14). Methane emissions are defined by a simplifying assumption using salinity level. Tier 1 approaches include a positive value for emissions at salinities that are below half that of seawater, and zero emissions at higher salinities. On the basis of the C-CAP data, all wetlands delineated as palustrine were given a positive CH_4 emission value, and estuarine class wetlands a zero, using the IPCC default factor[4] of 193.7 kg CH_4 ha^{-1} yr^{-1}. Considering wetland loss, a tier 1 assumption was applied such that salinity conditions were unchanged and therefore CH_4 emissions were assumed to be zero with the conversion of VCW–UOWCW. Mineral and organic soils are not differentiated. The global warming potential factor of 25 from the IPCC's Fourth Assessment Report was used to convert CH_4 values to CO_2e values[20].

Nitrous oxide emissions. The methodology to estimate N_2O emissions from aquaculture in coastal wetlands follows the guidance in the Wetland Supplement applying country-specific fisheries production data, the IPCC tier 1 default emission factor of 0.00169 kg N_2O–N per kg fish produced[4] and aquaculture data are from the annual NOAA fisheries report[21]. The global warming potential value of 298 from the IPCC's Fourth Assessment Report is applied to derive the CO_2e values from N_2O emissions[20].

Uncertainty estimates. Underlying uncertainties in estimates of soil carbon stock changes and CO_2 flux include errors in uncertainties associated with tier 2 literature values, assumptions that underlie the methodological approaches that were applied, and uncertainties linked to the interpretation of remote sensing data, including differentiation of palustrine and estuarine community classes. Uncertainties for the CH_4 flux are the tier 1 default values that are reported in the Wetlands Supplement, including the uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands, conversions between vegetated and open-water saline wetlands, and activity data used to apply CH_4 flux emission factors (delineation of an 18-ppt boundary). For N_2O emissions, uncertainty estimates are based on the tier 1 default 95% confidence intervals that are provided in the Wetlands Supplement.

Quality assurance/quality control and verification. The NOAA provided the national LIDAR dataset, tide data and C-CAP land cover and land-cover change mapping data, all of which are subject to agency internal quality assurance and quality control assessments. Soil carbon stocks, emission and removal data were based on peer-reviewed literature and CH_4 emission factors were derived from the IPCC Wetlands Supplement. NOAA provided an internal quality assurance and quality control review of reported data from fisheries data. The coastal wetlands inventory team consulted with the coordinating lead authors of the Coastal Wetlands chapter of the IPCC 2013 Wetland Supplement on which fisheries production data to include in reporting.

Data availability

Some of the data that informed this analysis are included in the US Greenhouse Gas Inventory (see previously published studies[5,6]). Other data can be made available upon request to the corresponding author (S.C.).

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