Title
Carbon Sequestration and Subsidence Reversal in the Sacramento–San Joaquin Delta and Suisun Bay: Management Opportunities for Climate Mitigation and Adaptation

Journal
San Francisco Estuary and Watershed Science, 20(4)

Authors
Windham–Myers, Lisamarie
Oikawa, Patty
Deverel, Steve
et al.

Publication Date
2023

DOI
10.15447/sfews.2023v20iss4art7

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Science Program and UC Davis Institute for the Environment

SPECIAL ISSUE: STATE OF BAY-DELTA SCIENCE

Carbon Sequestration and Subsidence Reversal in the Sacramento–San Joaquin Delta and Suisun Bay: Management Opportunities for Climate Mitigation and Adaptation

Lisamarie Windham-Myers *[1], Patty Oikawa[2], Steve Deverel[3], Dylan Chapple[4], Judith Z. Drexler[5], Dylan Stern[4]

We assessed nature-based solutions to climate mitigation and adaptation in the Sacramento–San Joaquin Delta and Suisun Bay and made the following conclusions.

- Restoring aquatic habitats in the Sacramento–San Joaquin Delta can reduce current greenhouse gas emissions, while providing additional ecosystem benefits to wildlife and water management.
- Hydrologic management (through agriculture, subsidence reversal, and tidal reconnection) is the dominant pathway to increased carbon sequestration and reduced methane emissions.
- The largest uncertainties in 40-year (market-based) climate mitigation estimates derive from uncertainties in flow and water operations, which drive projections of aquatic habitat extent and condition.

SFEWS Volume 20 | Issue 4 | Article 7
https://doi.org/10.15447/sfews.2023v20iss4art7

* Corresponding author: lwindham-myers@usgs.gov
1 Water Resources Mission Area, US Geological Survey Menlo Park, CA 94025 USA
2 Department of Earth and Environmental Sciences, California State University, East Bay Hayward, CA 94542 USA
3 HydroFocus, Inc. Davis, CA 95616 USA
4 Delta Science Program, Sacramento, CA 95814 USA
5 California Water Science Center, US Geological Survey Sacramento, CA 95819 USA

ABSTRACT

The aquatic landscapes of the Sacramento–San Joaquin Delta (hereafter, the Delta) and Suisun Bay represent both a significant past and future soil carbon stock. Historical alterations of hydrologic flows have led to depletion of soil carbon stocks via emissions of carbon dioxide (CO_2), and loss of elevation as a result of subsidence. Optimizing ecosystem hydrology in the Delta and Suisun Bay could both reduce and reverse subsidence while also providing significant opportunities for climate mitigation and adaptation. Emissions of greenhouse gases (GHGs)—notably CO_2, methane (CH_4), and nitrous oxide (N_2O)—contribute to global warming at different rates and intensities, requiring GHG accounting and modeling to assess the relative benefits of management options. Decades of data collection, model building, and map development suggest that past and current management actions have both caused—and can mitigate—losses of soil carbon. We review here the magnitude of potential GHG offsets, management options that may be achievable, and trade-offs of carbon storage under different land management. Using a land-use/land-cover framework to assess these management options, we describe the potential of three interventions (impoundment to reverse subsidence, agricultural management, and tidal reintroduction and/or maintained connectivity), both in acreage and radiative balance to clarify their relative influence on the region's GHG balance today and in relation to its millennial history. From floodplains to farming to floating aquatic vegetation, we find specific scalable strategies to manage hydrology that can alter regional GHG balance. Preservation of soil carbon stocks and restoration of net atmospheric CO_2 fluxes into soils are the primary route to net negative emissions in the Delta and Suisun Bay, with CH_4 emission management occurring in a supporting role. Over a 40-year horizon of climate-mitigation markets, the resilience of different aquatic habitats introduces the most uncertainty, from expected and unexpected hydrologic changes associated with land, ocean, and operational water flows.

KEY WORDS

greenhouse gas, soil carbon, hydrology, wetland, land management, aquatic ecosystem, biogeochemical, methane, carbon dioxide, nitrous oxide

INTRODUCTION

Background on Coastal Wetland Carbon Sequestration

Carbon (C) dynamics on managed lands are one type of natural climate solution considered within a portfolio of climate mitigation and adaptation responses (Fargione et al. 2018). Net ecosystem exchange (NEE) of carbon dioxide (CO_2) with the atmosphere is the dominant C flux in most land and aquatic ecosystems; biomass accumulation in wood and/or wood products, for example, is a negative emission (uptake) storage term for CO_2, as is soil C accumulation. Positive emissions of CO_2, however, also occur when carbon stocks are lost, such as through burning or drainage. Carbon stock loss in agricultural, forestry and other land uses (AFOLU) is currently responsible for 25% of the rise in atmospheric CO_2 stocks, globally, and is distinctly related to land-management decisions (Canadell et al. 2007).

Aquatic ecosystems are capable of negative CO_2 emissions (uptake and long-term soil C storage; USGCRP 2018), and thus can be used as a management tool to address climate mitigation goals. At the same time, aquatic ecosystems are particularly capable of anaerobic microbial activity in benthic sediments, yielding significant methane (CH_4) fluxes (Rosentreter et al. 2021). Soil microbial control of organic C fluxes is the dominant determinant of whether an aquatic ecosystem serves as a long-term greenhouse gas (GHG) source (e.g., CH_4 emission, soil oxidation and CO_2 emission) or sink (e.g. belowground productivity, soil C storage). Compared with CO_2, the metabolic products CH_4 and nitrous oxide (N_2O) are both more powerful GHGs (gram for gram) than CO_2 but also are shorter-lived in the atmosphere. As such, over 100-year time-frames, CH_4 and N_2O are, respectively, 21 and 310 times more powerful GHGs than CO_2 (IPCC 2014), and even more powerful-over a 20-year time-frame (56 and 298 times, respectfully; Abernethy and Jackson 2022). A further complication of aquatic ecosystems is that hydrologic flows through wetlands can carry C compounds in or out, to other environments, thus complicating the borders of land-use-based GHG accounting (Ward et al. 2016; Richardson et al. 2020). When all accounting is considered, the radiative balance of a wetland is determined ultimately by time scales of atmospheric and soil fluxes, spatial scales used within watersheds, and relative emissions of different gases, including negative emissions (removals from the atmosphere). Despite these accounting uncertainties with boundaries and anaerobic processes, aquatic ecosystem C dynamics are recognized as globally significant, with wetlands representing roughly 30% of global soil C stocks (Page et al. 2014), and 30% of global emissions of CH_4 (Saunois et al. 2016). Among all wetland habitats, coastal wetlands, which are formed by land–sea interactions, have the most potential to be managed to mitigate future climate changes, and the Sacramento–San Joaquin Delta landscape represents a particularly influential nexus of historical and future management opportunities to mitigate and adapt to future climate changes.

Coastal lands are among the most under-recognized C sinks globally and regionally (Windham–Myers et al. 2018a). Rates of organic C storage in coastal soils are positively related to sea level rise (SLR) at short and long time-frames (Herbert et al. 2021; Rogers et al. 2019), and thus wetland soil accretion is considered one of the few negative feedbacks of climate change (Kirwan and Megonigal 2013). Human alteration of the landscape is the primary limitation of coastal C sequestration (Spivak et al. 2019)—leading to barriers to marsh migration (Thorne et al. 2018), eutrophication-enhanced emissions of CO_2 (Deegan et al. 2012) and N_2O (Moseman–Valtierra et al. 2011), drainage-enhanced soil oxidation (Drexler et al. 2009a, 2009b), lateral C loss (Richardson et al. 2020), and impoundments that promote CH_4 emissions and limit sediment accretion rates (Kroeger et al. 2017). Given the global dominance of these landscape alterations, especially in California (Cloern et al. 2021), management is urgently necessary to restore coastal carbon sinks in aquatic habitats. Fortunately, there are many opportunities to use restoration and land management to accelerate climate mitigation and adaptation at the same time.

The Sacramento–San Joaquin Delta (hereafter, the Delta) is a coastal environment with a broad range of natural and human-induced drivers. This dynamic region sits at the confluence of the Sacramento and San Joaquin rivers as they enter the San Francisco Estuary (estuary), and its extent is thus bounded by its relative elevation and intersection of hydrologic drivers from rivers as well as the Pacific Ocean (Goman and Wells 2000; Drexler et al. 2009a). Globally, all deltaic systems share similar geologic ontologies, having emerged following the relative stabilization of sea level roughly 6,000 to 7,000 years ago (Bianchi 2018) and expanding or contracting based on varied geomorphic forcings. The Delta has had a sequence of deltaic footprints as a result of climate and ocean drivers, as well as tectonic forces (Atwater et al. 1982). Only through multi-disciplinary reconstructions and models have we quantified changes in the character of aquatic habitats and their distribution through time and space (Whipple et al. 2012; Cloern et al. 2021, Boyer et al., this issue).

The Delta developed carbon-rich soils over millennia, ranging from marginal floodplain organic-rich mineral soils to massive Central Delta peats. Peat soils, especially those in boreal or coastal peatlands, comprise one-third of the global carbon storage in soils (500 Pg [1 petagram = 10^{12} kg]; Page et al. 2016), which itself is twice the size of the atmospheric reservoir of carbon. The histosols in peatlands allow long-term, millennial storage of organic compounds, essentially removing fixed carbon from annual carbon cycle dynamics (Bridgham et al. 2006). Peatlands worldwide occupy about 3% of the land surface, but their biomass and soil stocks contain almost 20% of all terrestrial organic carbon (Loisel et al. 2014). In the Delta, peatlands and other tidally influenced soils accumulated approximately 200 Tg (1 Tg = 10^9 kg) of organic carbon over the last 6,700 years (Drexler et al. 2019), with soil extents both deep (up to 10 m) and expansive (nearly 500,000 acres; Atwater 1982). However, drainage of the peatlands, which began in the mid-19th century, resulted in the loss of approximately half the Delta's soil carbon stock (Drexler et al. 2019). This degradative process is on-going (Deverel et al. 2016) and has resulted in subsidence of Delta islands to elevations as low as 9 m below sea level (Deverel et al. 2020).

Greenhouse gas emissions to the atmosphere are primarily sourced by microbial activity, whereby microbial use of organic carbon compounds in soils lead to their complete mineralization (CO_2) or the creation of other GHG such as the secondary metabolic products CH_4 and N_2O. When oxygen is introduced to previously anoxic soils, microbial community metabolism accelerates, because the free energy yield of oxygen-based respiration is significantly greater than anaerobic respiration (such as fermentation). The step-wise matrix of free energy yielded through respiration by different terminal electron acceptors (TEAs)—from oxygen to nitrate, to iron

https://doi.org/10.15447/sfews.2023v20iss4art7

oxides, to manganese oxides, to sulfate—is the framework that regulates rates and pathways of organic matter degradation. When TEAs are not abundant, non-terminal pathways, such as methanogenesis, can compete successfully for electron donors such as acetate. Methane (CH_4) production is strongly predicted by anaerobic conditions, and notably the lack of TEAs, and can be emitted from saturated soils through diffusive processes, ebullition (bubbles), or through aerenchyma pathways in plants (straws). However, atmospheric emissions only occur when methane is not consumed within soils by methanotrophs or other oxidation processes (combustion). Similarly complicated, N_2O can be both produced and degraded by nitrifying and denitrifying bacteria, such that net emissions are balanced between competing rates. For these reasons, the reduction–oxidation potentials (redox) of soil and water profiles are useful to infer metabolic pathways, and thus project net rates of GHG emissions and soil carbon stabilization.

Recent studies suggest that carbon loss from wetland soils can be slowed or reversed through management interventions that involve manipulations of flows, vegetation, or nutrient status (see review by Moomaw et al. 2018). These interventions may target (1) enhancing CO_2 removal through photosynthesis and organic carbon burial, and/or (2) avoiding emissions of CO_2 from soil oxidation. However, the radiative balance of a given land use must also include estimates of CH_4 and N_2O (Bridgham et al. 2006). Therefore, a third intervention is: (3) reducing CH_4 or N_2O emissions over and above management of CO_2 emissions. While preventing loss of soil C stock through oxidation is a dominant means of reducing wetland GHG emissions (Pendleton et al. 2012), CH_4 emission management is increasingly being considered in global agreements for Reducing Emissions of Deforestation and Degradation (REDD+) climate mitigation offsets (Poulter et al. 2021). Lateral hydrologic fluxes of organic and inorganic carbon are only recently being considered for climate mitigation offsets, as a function of alkalinity or burial (Santos et al 2021).

Three Suggested Hydrologic Interventions

Across managed or "working" landscapes, such as the Delta and Suisun Bay, a wide range of opportunities exist to reduce GHG emissions, but a single consistent driver is hydrologic management. Based on current understanding and modeling capabilities, we specifically suggest three hydrologic interventions for consideration in the Delta and Suisun region (Figure 1).

First, targeted agricultural water management can enhance soil preservation through rewetting soils and reduce methane emissions with pulsed drying events (Figure 1A). **Second**, reversing subsidence through wetland restoration relies on temporarily impounding peatlands to allow peat re-establishment and accretion, until connectivity with the larger watershed is sustainable (Figure 1B). **Third**, tidal reintroduction allows hydrological connectivity to promote vertical accretion in intertidal and sub-tidal habitats while also restoring marine influence through tidal flows to supply sulfate and reduce CH_4 emissions. These three interventions have targeted places and time-frames and may not be compatible with current land-uses, water-needs, and/or wildlife management, yet consideration of their geomorphic and biogeochemical effects can inform decision-making. This wide range of aquatic habitats and management opportunities are limited to specific geomorphic regions of the Delta and Suisun Bay that constrain their sustainability over time and their modification potential (e.g., managed wetlands on deep sub-tidal lands; see Figure 2). Within each of these interventions, water management— including source, timing, depth, and frequency of flooding—plays a significant role in preventing soil organic carbon loss (subsidence), increasing future rates of atmospheric carbon sequestration, and reducing methane emissions. Because the distribution of these habitats is maintained by management operations and decisions, they can be managed to promote climate mitigation. For example, the California EcoRestore restoration initiative includes both tidal wetland restoration at intertidal elevations that can be planned and managed for sea level rise, and non-tidal freshwater wetlands on deeply subsided islands

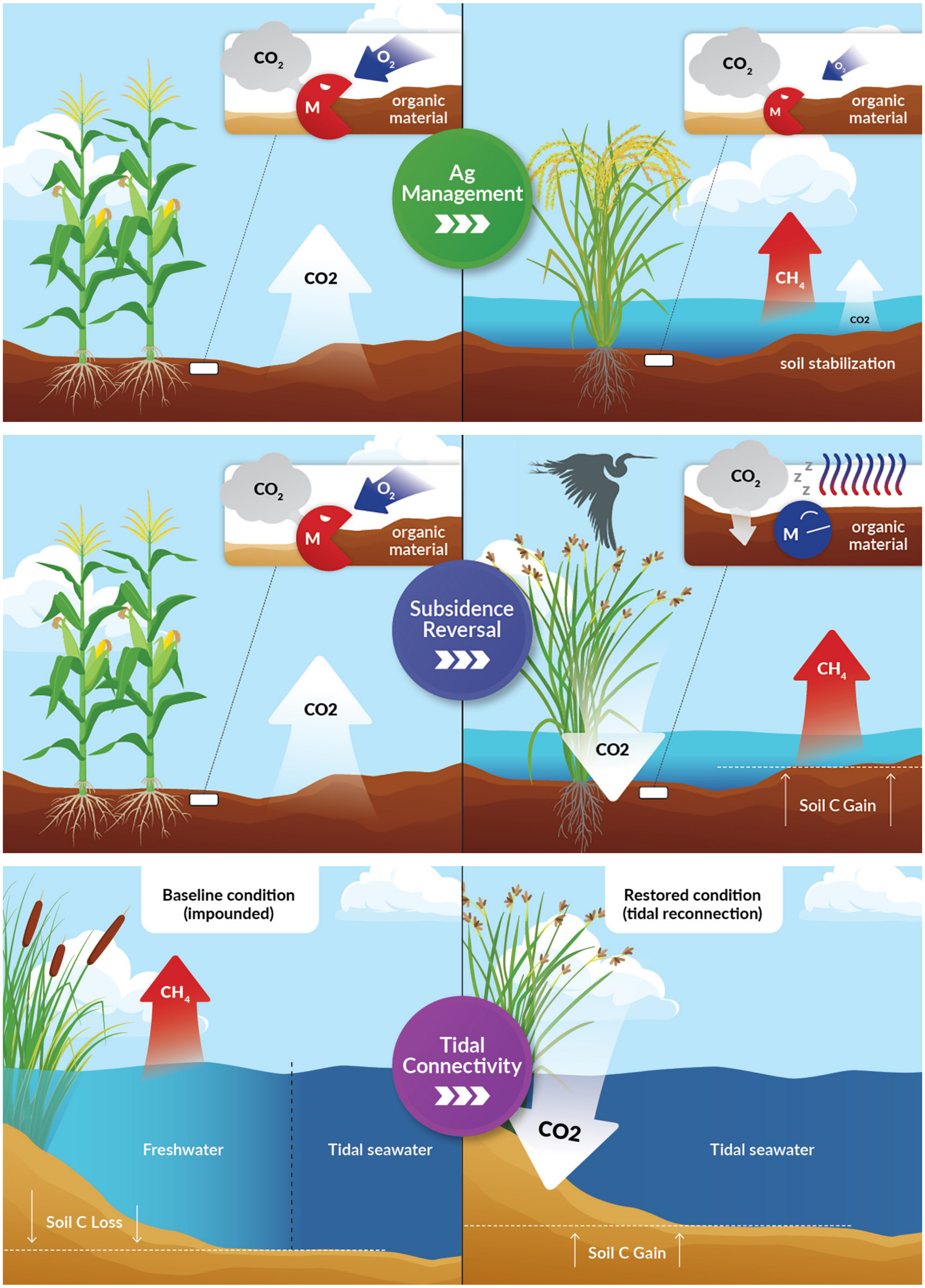

Figure 1 Three interventions, including (**A**) agricultural hydrologic management via flooding, such as in rice agriculture, (**B**) impounded wetland construction to reverse subsidence, and (**C**) tidal connectivity restored or maintained. M = microbial activity. *Source and credit: Figures adapted from Stern et al. (2022). Illustrated by Vincent Pascual, California Office of State Publishing.*

https://doi.org/10.15447/sfews.2023v20iss4art7

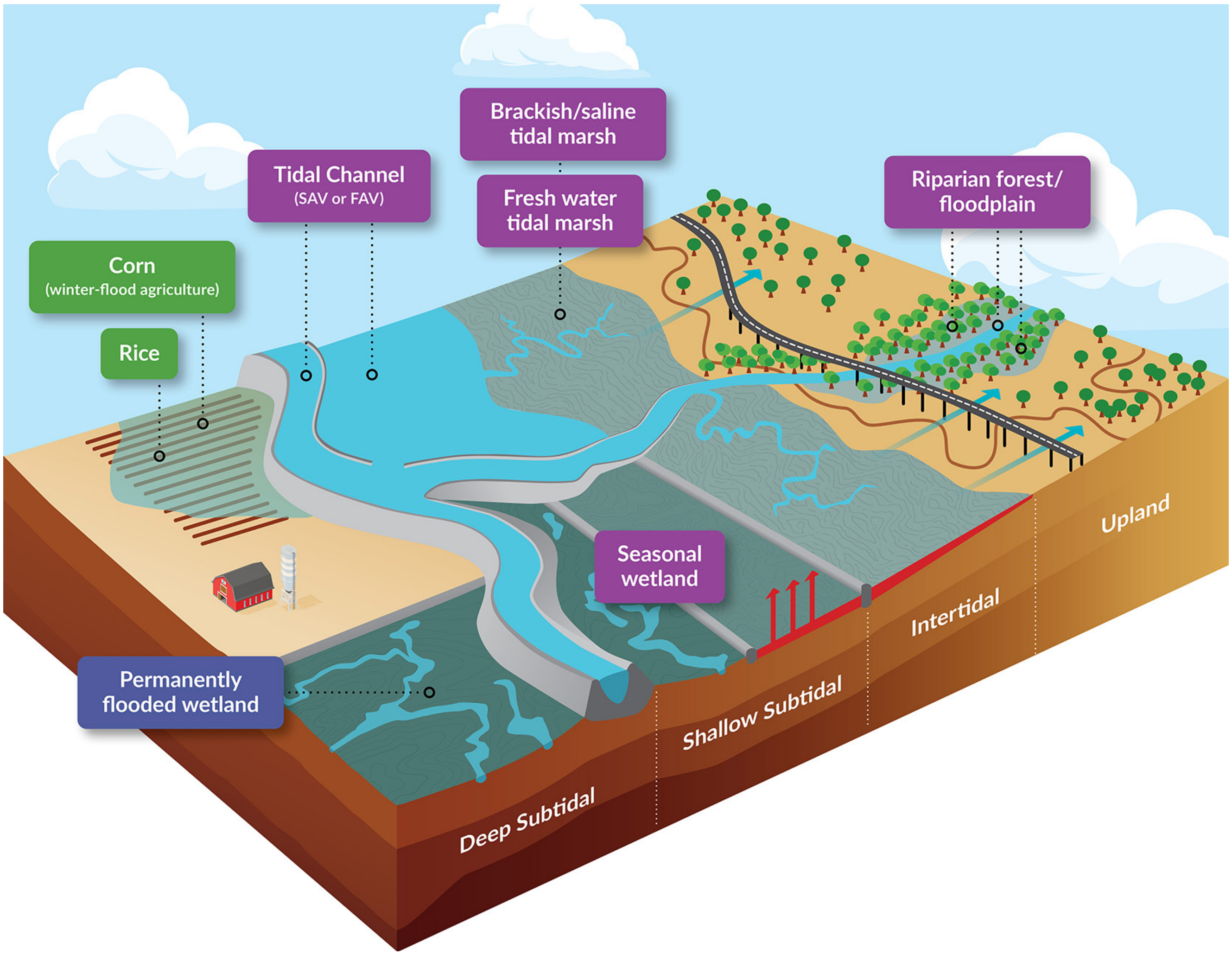

Figure 2 Land-use types of interest to carbon sequestration and/or GHG mitigation across the relative tidal elevation range in Suisun Bay and Delta lands. Corn indicates conventional row crops. Tidal channel refers to open-water aquatic habitats, whether deep or shallow (such as flooded islands) and which may be populated by submerged or floating aquatic vegetation (SAV and FAV). Permanently flooded wetland refers to wetlands impounded to reverse subsidence. Seasonal wetland refers to wetlands managed via freshwater flooding to benefit wildlife. *Credit: Illustrated by Vincent Pascual, California Office of State Publishing, adapted from SFEI.*

that are planned and managed to reverse subsidence. (California EcoRestore Projects; *https://resources.ca.gov/Initiatives/California-EcoRestore/California-EcoRestore-Projects*).

We review current understanding for the three aforementioned hydrologic interventions (Figure 1), and also how they are distributed over components of the Delta landscape (Figure 2). We focus on well understood actions within the current land-use context (Figure 3) but also review emerging GHG accounting benefits in three categories:

Three Categories of Emerging GHG Accounting Benefits

Agricultural Hydrologic Management to Limit CO_2 and Reduce CH_4 Emissions

The two most promising actions are:

- **Flooding agricultural fields**—Allowing flooding to return to lands that have been drained during periods of crop production. Because this action reflects rice cultivation (summer flooded) and winter flooded lands, it is the most spatially extensive as well as the most highly uncertain opportunity as fluxes associated with lateral (hydrologic, harvest) and anaerobic processes are condition-specific.

- **Intermittent drainage of rice fields**—Alternate wetting and drying (AWD) of rice fields, thus allowing cyclical surface flooding in summer and in winter to reduce methane emissions while supporting rice production.

Wetland Restoration to Reverse Subsidence through Impoundment, and Associated CO_2 Uptake

The single most effective action to regain elevation in sub-tidal lands is:

- **Impounded freshwater wetlands**—Establishing on subsided agricultural fields a permanently flooded, peat-building wetland that reverses subsidence

Preservation or Reintroduction of Tidal Exchanges for CO_2 Uptake and to Reduce CH_4 Emissions

In a highly managed environment with elevations within the tidal frame, any actions that reduce barriers to tidal exchange will lead to soil accretion and sulfate refreshment, which inhibit methane emissions.

- **Tidal restoration**—Reintroduce tidal flows in inter-tidal areas currently protected by levees.

- **Preserve tidal marsh (brackish/saline) processes**—Maintain intertidal, vegetated lands where marine-influenced salinity reaches above 0.5 parts per thousand annually. As per Drexler et al (2013), Delta wetland salinities are largely oligohaline (0.5 to 5 ppt), whereas Suisun Bay wetlands can exhibit mesohaline conditions (5 to 18 ppt).

- **Preserve freshwater tidal marsh processes—**Maintain intertidal, vegetated lands where marine-influenced salinity remains below 0.5 parts per thousand annually.

- **Preserve/expand riparian forest** (across geomorphically distinct floodplains)—Maintain floodplains with a significant tree canopy component sufficient to influence C stock accounting.

DELTA-SPECIFIC RANGES OF C STOCKS AND FLUXES

The Delta, as a seismically active interface of riverine and ocean influences, historically experienced rapid soil accretion rates, at times in excess of sea level rise (SLR; Malamoud–Roam et al. 2006). Following observations reported in Rogers et al. (2019), it is thus not a surprise that Delta soils have relatively high soil C densities, as a result of rapid preservation of organic matter in subsiding soil horizons (~0.04 + –0.01 g C cm^{-3} (Drexler et al. 2011), compared to a global mean for tidal wetland soils of roughly 0.03 g C cm^{-3} (Holmquist et al. 2018a, 2018b; see also Coastal Carbon Atlas [shinyapps.io]). Delta soil development has been driven by millennial-scale organic accumulation, mainly from *in situ* productivity, and inorganic sedimentation via suspended sediment from the greater watershed (e.g., Drexler et al. 2019). Bulk density and percent organic carbon (OC) observed in deep soil cores illustrate changing geomorphic settings and vegetation shifts apparently related to marine influences (Goman and Wells 2000; Drexler et al. 2009a; Fard et al. 2021). Deep cores consistently indicate long-term C preservation in marsh soils developed during the Holocene time-period. Radiocarbon dates indicate continuous processes of sediment and soil development over the past 6,800 years throughout much of the current land surface (Drexler et al. 2009a). Newer (<150 years ago) progressive land building on Delta and San Francisco Bay edges—so called “centennial marshes”—are much shallower and more mineral-rich than historical wetlands built under less disturbed conditions (Callaway et al. 2012). Figure 4 illustrates the soil OC densities observed in profiles in depths of up to 7 to 8 meters in four focal sites of the Delta. The relatively high OC densities observed (presented in the circled markers) in surface soils at Browns Island indicate rapid sedimentation and burial during

https://doi.org/10.15447/sfews.2023v20iss4art7

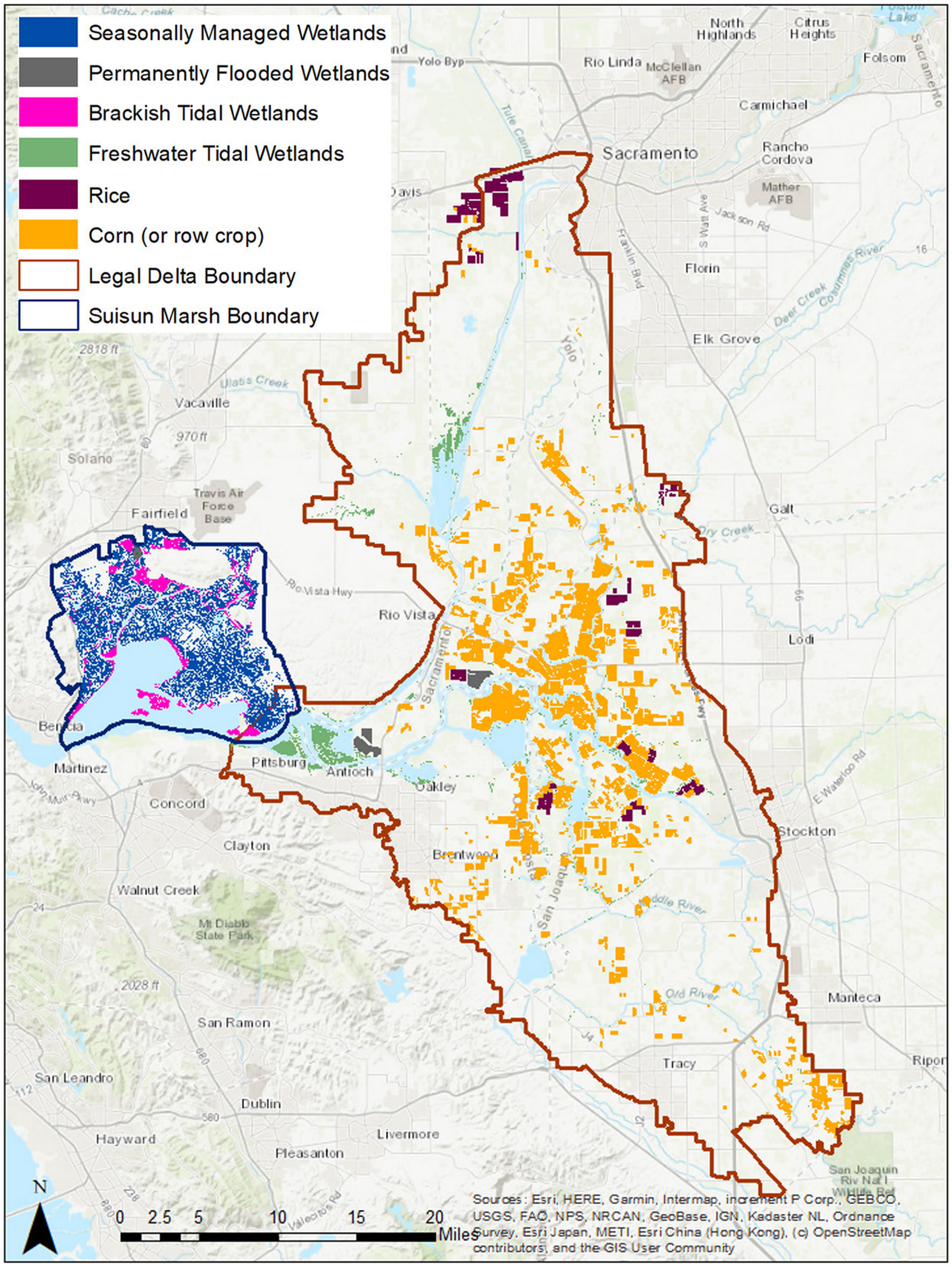

Figure 3 Natural ecosystems and managed lands in the Delta and Suisun Bay considered in this study of GHG-mitigation potential. Categories = (1) row crop agriculture (such as, corn), (2) rice agriculture, (3) permanently flooded wetlands (managed), (4) seasonally managed wetlands, (5) freshwater tidal wetlands and (6) brackish tidal wetlands. No distributions mapped for aquatic vegetation, either (7) submerged (SAV) or (8) floating (FAV), and distributions of woody trees considered as (9) floodplains with significant biomass carbon stocks. *Sources: Basemap and agriculture categories from Land IQ (2016). Freshwater wetlands (tidal and managed) from 2016 VegCAMP; brackish wetlands in Suisun from 2015 VegCamp.*

and after the California Gold Rush era (1850 to 1900).

Interconnected physical and biological processes of the historical tidal estuary were responsible for generating the Delta's globally significant peat deposits. Halting and/or reversing the continued loss of this peat deposit requires active intervention, as modern environmental and societal conditions constrain these natural processes (Loisel et al. 2021). Conceptually, the three classes of management actions discussed herein (Figure 1) are different ways to restore sustainable C storage processes across a highly disturbed and actively managed landscape. Considered sequentially, instead of spatially, these management actions are akin to a series of household plumbing goals: (1) stop the leak, (2)

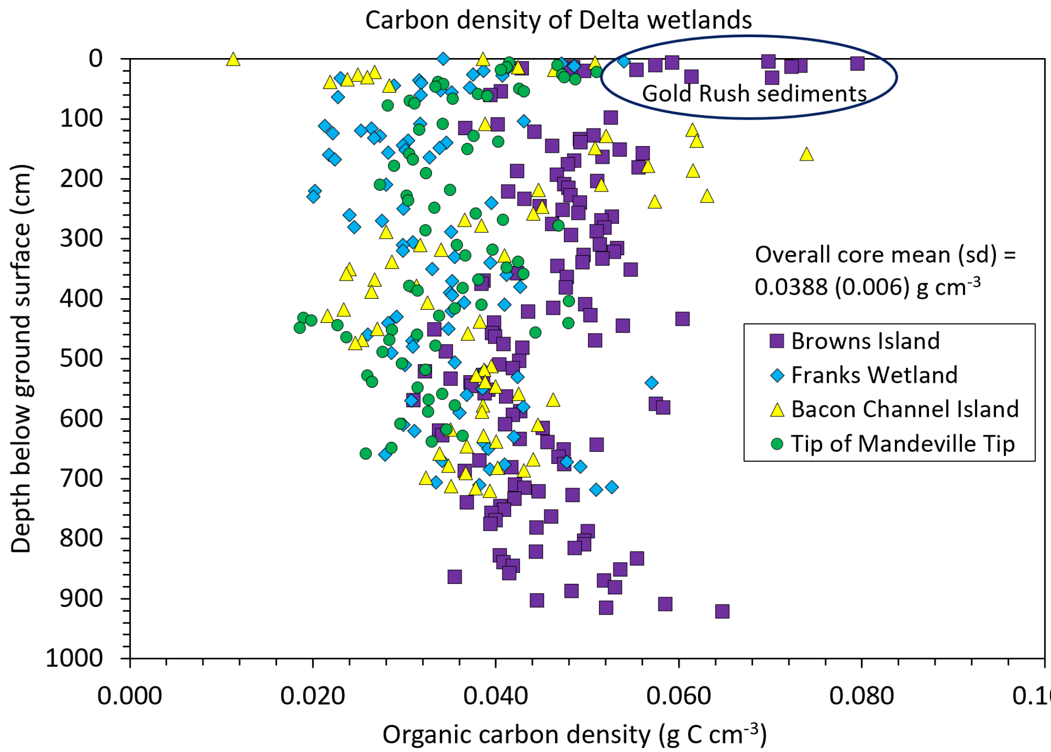

Figure 4 Carbon densities (calculated as organic carbon by weight x dry bulk density, in 2-cm increments) along soil profiles from four deep-soil cores collected in Delta wetlands. *Sources: Data from Drexler et al. 2009a, 2016.*

repair the structure, (3) reconnect flows. **Stopping the loss** of soil C by preserving the remaining stock of the historical soil carbon in the Delta is the single largest opportunity to make progress toward achieving carbon neutrality of Delta lands. Limiting oxidation or erosion-induced CO_2 off-gassing from wetland soils is akin to putting out "millions of small fires" (sensu NASEM 2019). Rates of CO_2 off-gassing through oxidation are greatest in freshly disturbed peat soils with relatively high organic carbon contents (Deverel and Leighton 2010), an uncommon condition now that the Delta has limited undisturbed land. However current rates of soil carbon oxidation remain concerning (losses of up to 4 cm y^{-1} and 1 kg C m^2; Deverel et al 2020), and action to avoid C stock loss is applicable broadly to wetlands across the entire salinity and geomorphic gradient from Suisun Bay (Siegel and Gillenwater 2020) to Bouldin Island (Hemes et al. 2019).

In addition to reducing soil C stock loss, gaining new C stocks through CO_2 sequestration in soils is possible through wetland enhancement and establishment. In fact, it is not just possible, it is among the only means of structural repair of land elevations in a peat landscape. Active primary productivity can lead to significant C storage in actively accreting wetlands (Callaway 2019). Of note, organic matter is volumetrically more dominant (up to 10-fold) in building elevations of tidal wetland soils than mineral inputs (Morris et al. 2016).

In addition to this one-dimensional growth of wetland soils upward, reconnecting tidal flows allows soil to accumulate C through expansion in three dimensions, with wetland migration and expansion outward increasing the wetland soil C stock through reestablishment at suitable elevations (such as on previous wetland soils) or progradation over Suisun Bay sediments

https://doi.org/10.15447/sfews.2023v20iss4art7

(outboard of current land edges; *https://www.ecoatlas.org/*). The fate of wetland soils, as a millennial-scale C sink, is very uncertain, because climate and land-use drivers play intertwined and critical roles in where and when tidal wetland processes remain sustainable. Projections of the future extents of wetlands is, thus, a key constraint to quantifying opportunities to sequester C (e.g., Pendleton et al. 2012; Swanson et al. 2014; Thorne et al. 2018).

Reconnecting tidal flows and other intermittent flooding opportunities also allow biogeochemical flushing and replacement of fresh electron acceptors (e.g., oxygen, nitrate, sulfate) that can inhibit methanogenesis, an important anaerobic process that occurs in tandem with soil C stabilization (Bridgham et al. 2008). Because GHG can also be mitigated-by reducing microbially-produced CH_4 emissions or N_2O emissions, hydrologic management can fine-tune biogeochemical poise to limit GHG emissions. One proposed opportunity is the reintroduction of sulfate from marine systems by returning regular tidal influence and thus marine-based salinity (namely sulfate ions) to otherwise freshened systems (e.g., Poffenbarger et al. 2011; Kroeger et al. 2017). This reintroduction can both restore geomorphic accretion of soil C (through sedimentation) and inhibit the soil methanogenic microbial pathway through substrate competition (e.g., acetate; Bridgham et al. 2018). Agricultural additions may also enhance sulfate supplies (Alpers et al. 2014), but the refreshment rate is seasonally variable, and it should be noted that it likely promotes mercury methylation in Delta soils (Marvin–DiPasquale et al. 2014). A second opportunity to reduce CH_4 emissions in the Delta, while allowing soil C stabilization, is intermittent drainage or flushing of anaerobic soils, which re-oxidizes TEAs (nitrate, ferric iron, manganese oxides, sulfate) that can inhibit rates of methanogenesis (e.g., McNicol et al 2017) and potentially reduce emissions; intermittent flooding (also termed alternate wetting and drying; AWD) may be applicable to both rice agriculture (e.g., Runkle et al. 2018) and impounded wetlands (e.g., Hemes et al. 2019), while still allowing C to be stabilized in soils, which reduces peat subsidence (e.g., Hatala et al. 2012).

Despite these promising land management options, their benefits and drawbacks are intertwined with modifying hydrology to promote climate mitigation and adaptation goals. A review of restored wetlands that occupy former agricultural land in the Delta (Hemes et al. 2019) illustrates the trade-offs of C sequestration and CH_4 production across a wide landscape gradient. For example, optimal long-term reduction of total emissions of C in soil requires permanent flooding, because seasonal flooding does not allow new C inputs to be stabilized, and thus does not allow for negative C emissions (Hemes et al. 2019; Bergamaschi et al. 2021). However, while permanent flooding clearly reduces CO_2 emissions (Miller et al. 2011; Anderson et al. 2016; Hemes et al. 2018), impoundment also generates some of the highest CH_4 emissions ever measured among natural land-covers (Knox et al. 2021). In contrast, alternating wetting and drying (e.g., seasonally or tidally) can reduce CH_4 emissions, but intermittent drying risks oxidating soils with vulnerable organic C (Günther et al. 2020). Optimal hydrological conditions for a minimal radiative balance (sum of relative GHG forcings) are site- and condition- specific, and likely to be determined largely by natural variability, rather than by management alone (e.g., Knox et al. 2015; Windham–Myers et al. 2018b; Valach et al. 2021).

While simple calculations of CO_2 equivalents are useful to evaluate the net climate effects of an action, a radiative balance approach is more relevant to decision-making. Two important considerations of manipulations on radiative balance are (1) the relative effect of a management action and (2) the time-frame of the effect of a management action. First, a manipulation does not have to achieve net negative C fluxes to produce a cooling effect; any change that lowers the net radiative balance is a climate mitigation. Second, all manipulations should be considered across a time-frame, and thus a cumulative metric of radiation balance; for example, a highly CH_4-emitting freshwater wetland can still have a cooling effect when considered over a millennial horizon. Figure 5A, which depicts modeled data from a well-studied freshwater tidal marsh (Virginia, USA; Neubauer 2021), illustrates how cumulative radiative forcing can be linearly positive with time for CH_4 and exponentially negative with time for CO_2, resulting in a "cross-over time" of, in this case, 850 years, at which point the system is in "radiative balance" before becoming net negative. The purpose of calculating cross-over times is to illustrate the importance of time-scales in cumulative radiative forcing, because emissions can be positive when a wetland is young and net CH_4 emissions are high but will eventually become negative as the net carbon stored overwhelms CH_4 emissions. Given that Delta wetland soils are up to 6,700 years old (Drexler et al 2009b), the historical Delta likely had a net atmospheric effect of "cooling" (negative radiative balance), despite continuous CH_4 emissions.

In the Delta, wetland restoration through impoundment on subsided soils may not recover the net cooling effect of the historical Delta, at least over short time-scales. Figure 5B illustrates radiative balance for three estuary restoration sites analyzed by Arias–Ortiz et al. (2021). The sites vary in their cross-over times, with the tidal restoration site (Eden Landing, south San Francisco Estuary) continuously negative as a result of tidal flushing and sedimentation, and the two non-tidal wetland restorations (Twitchell Island and Sherman Island) needing either 200 or 400 years (respectively) to reach a net negative emission for climate mitigation. Even so, compared to baseline conditions dominated by oxidation of organic soils, impoundments in the Delta that are highly managed to mitigate carbon exhibit a substantial improvement in the radiative balance (Hemes et al. 2019; Deverel et al. 2020).

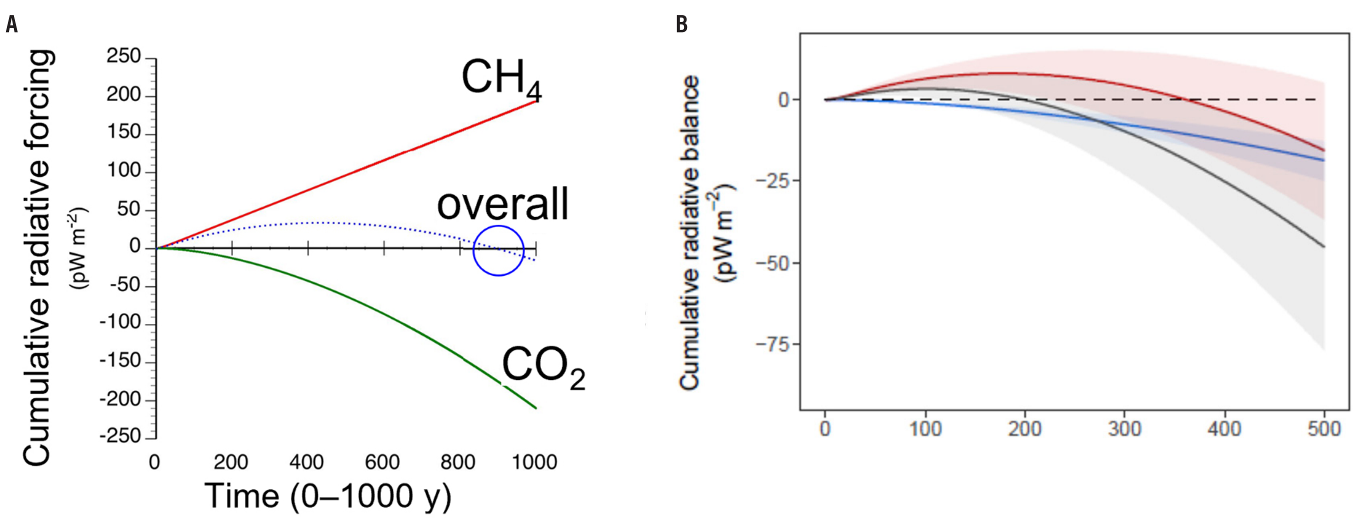

Figure 5 Cumulative radiative balance and cross-over times from net warming to net cooling effects. (**A**) Annual radiative balance for a freshwater tidal marsh in Virginia, reprinted from Neubauer 2021. The *blue circle* represents the crossover time for a freshwater marsh in Virginia, where emission balances reach net zero after 850 years. (**B**) Cross-over curves plotted by Arias–Ortiz et al. (2021) for tidal (*blue*) and nontidal (*red* and *black*) restoration sites in the estuary. Note that the tidal restoration site is net negative from inception, whereas the two nontidal sites take 200 or 400 years to cross over. For context, intact Delta marshes are over 6,000 years old and thus are likely to have crossed this threshold to "net cooling" more than 5,000 years ago.

https://doi.org/10.15447/sfews.2023v20iss4art7

DELTA-SPECIFIC MODEL KNOWLEDGE AND SCENARIOS OF CHANGE

The current rates of land-surface subsidence in the Delta—driven by climate, land-use changes, and modified flows—are unsustainable. Key indicators of unsustainable conditions include native species decline (e.g., Moyle et al. 2016), decreased arability (Deverel et al. 2015), increased pressure on levees and water supply vulnerability (Deverel et al. 2016), and large GHG emissions (Hemes et al. 2019). For example, using the SUBCALC model described in Deverel et al. (2016), and N_2O data described in Deverel et al. (2017b), Deverel et al. (2020) estimated the total annual GHG emission in the Delta at about 2 x 10^6 metric tons of CO_2 equivalents (MT CO_2 eq)—almost 1% of the entire state's GHG emissions, and the opposite direction of emissions estimated for a tidally connected Delta coastal landscape (–1.8 × 10^6 MT CO_2 eq; estimated from Graves et al. 2020), which functions as a carbon sink.

Multiple publications have demonstrated the GHG and subsidence-reversal benefits of rewetting Delta peat soils (e.g., Miller et al. 2008; Miller et al. 2011; Knox et al. 2015; Anderson et al. 2016; Windham–Myers et al. 2018b; Valach et al. 2020). Recently, Hemes et al. (2019) synthesized the GHG emission responses from converting exposed Delta soils to wetlands. The analysis, based on 36 site-years of CO_2 and CH_4 ecosystem flux data, revealed that subsidence-reversal projects significantly influenced GHG emissions. Direct measurements and model outputs by Miller et al (2008) and Deverel et al. (2014), respectively, indicate that deeply subsided, highly organic Delta soils managed to reverse subsidence can exhibit about 3 cm of accretion per year, with net annual C sequestration benefits of up to 20 tons of CO_2 eq per acre per year (Miller et al. 2011; Deverel et al. 2020). The long-term projections of these restoration trajectories and geomorphic model outcomes are unknown (Mount and Twiss 2005) with several important constraints on rates of subsidence reversal and marketable C sequestration (Bates and Lund 2013).

Little progress has been made in reducing, stopping, or reversing subsidence of organic soil in the Delta (Madani and Lund 2012). This is the case despite substantial evidence for increasing risks to the state's economy and water supply, the unsustainability of current elevations under the status quo, and evidence for the benefits of alternative land uses (Loucks 2019; Deverel et al. 2020). Economic incentives are necessary for land-owners and agricultural producers to convert to more sustainable land uses (Ingebritsen et al. 2000). Potential mechanisms for economic incentives include income from rice cultivation, economic use of wetlands, the California low carbon fuel standard, and the carbon offset market. Deverel et al. (2017b) presented a vision of a mosaic of subsidence-mitigating land uses that includes rice agriculture and wetland management that can provide reasonable agricultural income and a substantial GHG-reduction benefit. Wetlands also can provide a water-quality benefit by filtering agricultural drainage waters. The primary impediments to large-scale rice cultivation and wetland restoration on Delta lands are necessary investments in infrastructure and machinery, and cultural values associated with maintaining historical working landscapes (e.g., Baker et al. 2020).

Modeling presented in Deverel et al. (2014) suggested that accretion in impounded marshes on Delta islands (Ryer, Grand, Tyler, and Staten islands) and large areas in the southwestern, northern, eastern, and southeastern margins of the Delta may restore elevations to projected sea level within 50 to 100 years, assuming global SLR projections at current rates of 3 mm y^{-1}. Most of the central Delta would require 150 to 250 years, with many hazards (e.g., earthquakes, drought) limiting the likelihood of recovering elevation- (e.g., Bates and Lund 2013). In the western Delta where there is heightened interest in mitigating subsidence because of the water supply's vulnerability, model results indicated that a large portion of Sherman Island could be restored to projected sea level within 50 to 150 years. Deeply subsided portions on the southwestern and southeastern parts of Sherman would require 150 to 200 years to reach sea level. Large portions of Jersey and Bethel islands could be restored to sea level within 51 to 100 years. Small areas on Bradford, Twitchell, and Brannan islands, and Webb Tract can accrete at rates to reach sea level in 51 to 100 years, but most of the area on these islands is deeply subsided and would require 150 to 250 years.

While permanently flooded managed wetlands are a large source of CH_4 (Hemes et al. 2019), previous research has shown that brief periods of water table draw-down can significantly reduce CH_4 emissions, similar to strategies used in rice management often referred to as "Alternate Wetting and Drying" or AWD (Runkle et al. 2018). For example, a managed flooded peatland on Twitchell Island showed 35% lower annual CH_4 emissions during a year in which the water table was often lowered below the soil surface (six events each ranging between 2 to 11 days) compared to years without water table draw-down (Oikawa et al. 2017). However, we emphasize that water table draw-down needs to be short in duration (ideally 1 to 5 days), as longer-term draw-down leads to significant aeration of the soil, high soil CO_2 flux, and reduced soil accretion (Huang et al. 2021, Drexler et al. 2013; Günther et al. 2020). Focusing on individual gas fluxes informs model development but lacks the integrated assessment necessary for calculating radiative forcing of optimal hydrologic management.

Reduced emission of N_2O can be a small but easily manipulated source of climate mitigation. Because N fertilization stimulates nitrification and denitrification (Moseman–Valtierra et al. 2011) and N_2O emissions arise from incomplete denitrification, N_2O emissions can be reduced through nutrient management (Mozdzer et al. 2010). While these offsets of N_2O are often very small in magnitude (~1 to 10 mg N_2O m^{-2} d^{-1}), the magnitude by which N_2O influences radiative balance (298-fold greater impact than CO_2 over 100 years) suggests that nutrient management may provide benefits for climate mitigation in addition to reduced eutrophication and water-quality issues (Burgin et al. 2013). Anthony and Silver (2021) intensively sampled drained peatlands and identified significant N_2O emissions in the Delta's agricultural soils. Additional studies, globally, of extremes in flux distributions across landscapes (e.g., "hot-moments" and "hot-spots") suggest that N_2O emissions can also be offset by N_2O uptake in wetter components of the landscape (Groffman et al. 2009). Though ecosystem-scale N_2O uptake is difficult to observe (atmospheric concentrations of nitrous oxide are much lower than CO_2 and CH_4), N_2O fluxes alter radiative balance more strongly than CO_2 uptake on a weight basis. During conditions of high plant productivity N_2O uptake has been documented in both managed wetlands (Windham–Myers et al. 2018b) and rice fields (Ye and Horwath 2016) on Twitchell Island. Given the diurnal cadence of the N_2O fluxes in both flooded systems (e.g., uptake during daylight, no nighttime flux), physical (temperature or transpiration-related mass flow) or temperature-enhanced microbial uptake are predicted to be the source of daytime-observed N_2O sinks (e.g. Moseman–Valtierra et al. 2011; Martin et al. 2018).

Large, shallow open-water environments referred to as "flooded islands" are a landscape category unique to the Delta. Flooded islands (Franks Tract, Mildred Tract) are another potential land-cover type that may have potential increases in acreage in response to sudden levee failure from storms, earthquakes, or chronic levee instability. Considering the immediate soil-related GHG implications of allowing land to convert to open water, CO_2 emissions should halt (as oxidation stops) and yield to additional CO_2 uptake and carbon sequestration by floating aquatic vegetation (FAV) and submerged aquatic vegetation (SAV), with potentially significant, long-term carbon storage in bed sediments (Drexler et al. 2021). While there are flooded islands today in the Delta, and some evidence of autotrophic fluxes in their benthos (Cloern 2019), we do not have data or models to constrain such benthic fluxes (but see Damashek et al. 2015), nor do we have any data on the overall radiative balance of these environments. Future work invested in this knowledge gap would be helpful to constrain carbon budgets for the Delta under future climate scenarios.

https://doi.org/10.15447/sfews.2023v20iss4art7

Seasonally flooded wetlands in the Delta, and specifically those in Suisun Bay, are typically managed to benefit wildlife and could be managed to reduce GHG emissions and promote C sequestration. For example, seasonal flooding for waterfowl is common throughout US Fish and Wildlife Service refuges (Drexler et al. 2013b), and can be sufficient to limit oxidation when flooding is restored during hotter or drier conditions (e.g., Wang et al. 2019). More effectively, the return of tidal flooding and associated sediment delivery can promote soil accretion in these rapidly subsiding wetland parcels (e.g., Stralberg et al. 2011; Schile et al. 2014).

QUANTIFYING OPPORTUNITIES AND MONITORING NEEDS TO MANAGE GHGS FOR DELTA AQUATIC HABITATS

Here, we summarize market opportunities for managing aquatic habitats to mitigate and adapt to climate change, and quantify how different interventions affect GHG fluxes among the aquatic habitats of the Delta. Published data on GHG fluxes for the three targeted actions (Agricultural Management, Impoundment to Reverse Subsidence, Tidal Reconnection) are summarized in Table 1 for CO_2, CH_4 and N_2O. The projected effects of these actions are also scaled up in Table 1 using the map extents available. Finally, Table 2 provides a ranking of potential effect and uncertainty to guide data needs to support market opportunities among these nine landscape types. The independent calculations behind these summary tables are found in Appendix Tables A1–A3, for CO_2, CH_4 and N_2O, respectively.

We note here that while decades (collectively) of eddy covariance data within the Suisun–Delta complex are available to parameterize CO_2 fluxes in intertidal and permanently flooded managed wetlands, and protocols have been developed to model these rates (e.g., Oikawa et al. 2017), CH_4 and N_2O emission data are only available for some wetland categories within the Delta or can be predicted from elsewhere in temperate delta landscapes in the US. Of particular importance in the Delta is the proposed expansion of freshwater tidal habitats (DSC 2020), for which changes in annual flux rates of CH_4 and N_2O are highly uncertain in the literature (Windham–Myers et al. 2018a; Rosentreter et al. 2021) and are currently not sufficiently quantified to estimate the benefits of GHG mitigation in the Delta, as well as globally.

Agriculture Management (Winter-Flooded and Flooded-Rice Production)

With nearly 400,000 acres of non-flooded agriculture within the Delta, cropland is the single largest land-cover type that could be managed to mitigate GHGs. Conversion from row crops requiring a drained root zone (>1 m during the growing season) to rice cultivation is currently considered a climate mitigation offset within the methodology published by the American Carbon Registry (Deverel et al. 2017b). Deverel et al. (2016b) provided evidence for the subsidence-stopping benefit of rice cultivation on Delta peat soils, and Hemes et al. (2019) provided evidence for the net GHG benefit of conversion to rice. Multiple Delta land-owners are moving toward selling offsets within the voluntary carbon market to convert their land to rice farming.

Winter flooding is often used to reduce crop residues, as well as expand habitat for migratory waterfowl. While initially considered a way to enhance soil preservation, recent studies (e.g., Bergamaschi et al. 2021; Hemes et al. 2019) show that the net impact of winter flooding only minimally prevents soil oxidation. Further, because Delta winters are fairly warm, winter flooding promotes CH_4 emissions at levels that exceed tidal lands ($13\,g\ CH_4\ m^{-2}\,y^{-1}$). Gas flux measurements in Bergamaschi et al. (2021) illustrate that flooding temporarily inhibits oxidation of soil C, but, upon drainage, cumulative emissions rapidly catch up. Ultimately, net annual C balances have not been shown to decrease in response to winter flooding. While wildlife and levee protection may be enhanced by raising water tables during winter conditions, this mechanism ultimately lacks support as a GHG management intervention and is thus not considered marketable at this time. Targeted research on the timing and depth of flooding could quantify the potential of this common intervention.

Intermittent flooding, or AWD, is gaining acceptance as a way to mitigate rice crop GHG emissions and other biogeochemical challenges (Fertitta–Roberts et al. 2017; Tanner et al. 2018). Crop yield may be maintained sufficiently with periodic drainage events that shift the biogeochemical poise away from methanogens and toward microbes using TEAs (e.g., oxygen, nitrate, iron oxide, manganese oxide, sulfate). The concept may be expanded to permanently flooded wetlands, but it is critical to specify an optimal hydroperiod, because the wetland "product" is peat, and peat organic matter is likely lost rapidly when water tables fall (Oikawa et al. 2017; Valach et al. 2020).

On agricultural lands, switching to managing the wetland for rice farming is not the only way to reduce soil oxidation. Marginal lands can be considered for hydrologic restoration as well, not as direct GHG sinks but as collateral in providing C sequestration benefits at a landscape scale. As these lands continue to subside as a result of organic matter oxidation and compaction, they become wetter and increasingly mineral-dominated. Thus, the soil quality becomes marginal, too wet to farm conventionally, and without a known carbon benefit if preserved. For example, exposed remnants of sand dunes are evidence of topsoil oxidation. With the high permeability of the dunes, restoring the water table for these lands could help protect soil carbon stocks in neighboring parcels. Thus, they could be considered a "no regrets solution" for farmers receiving no other obvious benefit to active management (Deverel et al. 2020).

Reversing Subsidence through Restoring Peatland

An alternative fate for the 415,000 acres of non-flooded agriculture is to restore wetland to accrete peat. The protocol for restoration of California Deltaic wetlands (Deverel et al. 2017b) has facilitated the verification of GHG reductions for restored wetlands on state-owned Delta islands and may lead to trading of C-offset credits in the voluntary market. The voluntary carbon market provides C-offset credits for buyers who are not necessarily legally obligated to offset their C footprint. Approximately 1,700 acres of wetlands have been registered and in 2020 reduced GHG emissions by a verified 52,000 $MTCO_2$ eq, as issued by the American Carbon Registry within the voluntary carbon market. These offset credits can yield income generally commensurate with current agricultural lease values on state-owned islands at a price of about USD 7 to 10 per $MTCO_2$ eq (DSC 2020). However, the 40- to 100-year permanence requirement can be an impediment. Transition from the voluntary to the California C-offset compliance market may occur as early as 2024. The California compliance (cap-and-trade) market provides offers for regulated entities that are required to reduce their C footprint. A small percentage of the footprint can be offset with C credits. Participation in the compliance market will likely result in higher prices per $MTCO_2$ eq. (> USD 15), and prices are projected to rise to over USD 30 per $MTCO_2$ eq. within 10 years, which is more commensurate with current agricultural commodities and hence will likely increase land-owner participation.

Reconnecting Hydrology and Maintaining Connectivity

While the Delta was once a hydrologically connected and diverse landscape (Whipple et al. 2012), the 2,000 km^2 landscape has shifted to two dominant land-cover types: agricultural land (~1,750 km^2) and open water (~250 km^2). Very few parcels of agricultural land are poised for tidal reconnectivity because of historical elevation loss and operational constraints (Deverel et al. 2020). Thus, reconnectivity is largely an intervention for less-altered landscapes, such as seasonal wetlands and floodplains, notably those in the west (Suisun) and north Delta zones. We review here benefits for preserving or restoring tidal flow to lands capable of maintaining intertidal elevations through re-establishing geomorphic wetland accretion processes. We also quantify the potential for hydrologically connected sub-tidal environments (open water) to be considered as a GHG mitigation opportunity.

Intertidal wetland restoration and preservation is a primary goal of EcoRestore, because since

https://doi.org/10.15447/sfews.2023v20iss4art7

1850, 98% of intertidal lands have been lost to landscape modification (Whipple et al. 2012). Protecting and allowing expansion of current brackish marshes and freshwater tidal marshes are paramount both for C stock preservation as well as continued atmospheric drawdown of CO_2. The net negative emission benefits of tidal wetlands are well documented globally and, in the Delta, through both soil core evidence (Callaway et al. 2012; Drexler et al. 2009a) and continuous gas flux measurements at a central reference site (Rush Ranch in the San Francisco Bay National Estuarine Research Reserve (SFBNERR); Windham–Myers et al. 2018a). Results from reference marshes indicate reasonable expectations in wetland restoration interventions for climate mitigation. Thus, documentation of net ecosystem carbon budgets (NECB) and minimal CH_4 emissions enable potential participants to be confident about market implementation.

When a leveed wetland is reconnected to tidal action, at least three controls are activated that decrease the radiative balance of a wetland (i.e., make it less of an atmospheric C source).

First, sedimentation rates are enhanced until intertidal elevations are restored (e.g., Williams and Orr 2002), which contributes to lateral and vertical land building. Carbon accumulation in recently restored wetlands often exceeds rates observed in extant wetlands (Sutton–Grier and Moore 2016).

Second, in addition to preserving externally supplied (allochthonous) organic C through sedimentation, intertidal wetlands can have exceptionally high primary productivity and thus atmospheric CO_2 uptake, maintained by tidal refreshment.

Third, the benefit of tidal reintroduction is the microbial inhibition of CH_4 production through refreshment of electron acceptors, especially sulfate, a dominant component of marine-based salinity. This is specifically useful in the more saline components of the estuary, such as Suisun Bay (because the Delta peat's 6,700-year history is largely of tidal freshwater soil formation; Drexler et al 2013).

The Suisun seasonal wetland complex is the single largest region capable of significant GHG modification by tidal reintroduction, as evident in results from models that draw upon copious data from the SFBNERR Rush Ranch reference site (Schile et al. 2014; Byrd et al. 2016, 2018; Knox et al. 2018; Bogard et al. 2020). Continued data collection there and at restored sites at opposite ends of the salinity spectrum—saline marsh at Eden Landing and freshwater tidal marsh at Dutch Slough—are providing evidence for robust uptake of CO_2 and marginal emissions of CH_4. It is notable that in Table 1 we use literature data from the US East Coast and Gulf Coast to estimate freshwater tidal wetland radiative balances (Virginia and Louisiana, respectively), but this may under-represent fluxes in Pacific Coast freshwater tidal wetlands. The Delta's tidal freshwater wetlands present the highest aboveground biomass values for all wetlands in the US (Byrd et al. 2018), and the rate of carbon dioxide exchange (Net Ecosystem Exchange, NEE) we report in Table 1 may be underestimated. Monitoring data for Delta-specific wetlands can greatly improve confidence in developing models of GHGs. Of particular concern is strong interannual variability necessitating multi-year characterization of GHG fluxes (e.g., Windham–Myers et al 2018a).

Fourth, C storage provides hydrologic reconnection in wood growth in riparian forests, which has limited current distribution, but represents a unique carbon storage term that benefits wildlife (Dybala et al. 2019). Despite poor reporting of soil C storage within riparian forests, we include this land use to highlight the potential for tree canopies to sequester C. With a canopy sequestration rate of up to 1 kg C $m^{-2} y^{-1}$, and aboveground biomass carbon densities that exceed 20 kg C m^{-2}, potential sequestration in riparian biomass may be nearly equivalent to the top meter of intertidal soils (Matzek et al. 2018). Thus, riparian lands are unique among aquatic Delta landscapes in having a significant C sink in woody plant cover, despite a limited soil stock. We estimate that afforestation in riparian habitats may sequester C at rates similar to soil accretion (Table 1).

We lack complete reporting in Table 1 for the effects of open-water environments, because they are difficult to characterize for net climate mitigation benefits, despite their abundance in the Delta and demonstrated ecosystem services (Drexler et al. 2021). Subsurface conditions are not amenable to Land Use/Land Cover (LULC) mapping but may be modeled using hydrodynamically spatially explicit models. Open-water environments may or may not have aquatic vegetation, either FAV or SAV. While FAV- and SAV-dominated habitats are abundant (2,266 acres FAV, 10,927 acres SAV; Ustin et al. 2021; also see Boyer et al., this issue) and may be able to store significant amounts of C per unit area (up to 200 g C $m^{-2} y^{-1}$; Drexler et al. 2021), they are temporally variable, unpredictable, and actively managed because of the dominance of invasive species (Conrad et al., this issue). Still, as tidally connected, depositional environments, C sequestration benefits are likely from their accretion potential. FAV- and SAV-dominated habitats are currently unrepresented in mitigation strategies (Morin et al. 2017); a key limitation for their inclusion is uncertainty in their distribution, uncertainty in their net atmospheric exchanges (e.g., CO_2 and CH_4), and the invasive nature of the species currently established.

Two categories at opposite ends of the intertidal gradient—deep channels and uplands—are not represented at all within Table 1 but are conceptually important for future planning and full accounting. These include (1) benthic soil carbon stocks under open-water environments, from past CO_2 sequestration (e.g., Mildred Island and Franks Tract; flooded islands; Galloway et al. 2000), and (2) future CO_2 sequestration in transgressive uplands with potential future tidal wetland soil building (2022 personal communication between S. Siegel and LWM unreferenced, see "Notes"). The necessary hindcast and forecast models for these past and future fluxes do not exist but may provide insight for additional interventions. Further, flooding of Delta islands would fundamentally change the nature of all Delta land uses, so flooding cannot be considered in a vacuum (Mount and Twiss 2005).

Results and Ranking

Overall, the three hydrologic interventions discussed here (agricultural hydrology management, impoundment for subsidence reversal, hydrologic reconnectivity) can improve the radiative balance of Delta sub-habitats. As seen in Table 1, their net effect will be small (< 10%) as long as the status quo of conventional agriculture continues (here, estimated at a maximum of 3 MT CO_2 eq y^{-1}). Winter flooding as practiced does not appear to promote a shift in radiative balance, because of CH_4 production as well as a rapid rebound of soil oxidation rates upon drainage (Hemes et al. 2019; Bergamaschi et al. 2021). Rice agriculture can reduce peatland emissions (notably from flooding during the warmer growing season) but is only marginally more beneficial than conventional agriculture (1,860 vs 2,050 CO_2 eq $m^{-2} y^{-1}$). AWD can reduce this GHG footprint substantially, as much as 59% (Simmonds et al. 2015), but additional studies are needed on Delta soils. Notably, among all the LULC classes reported, brackish marshes are the only ecosystem that we can be certain have a current **net negative** emission, which is a result of high-frequency monitoring of NECB and CH_4 emissions (–1,011 ± 10^3 g CO_2 eq $m^{-2} y^{-1}$). All other sub-habitats are either **uncertain** (budget is not estimated because of lack of data, e.g., seasonal wetlands) or **net positive**, because of soil oxidation (CO_2; conventional agriculture, status quo) or estimated CH_4 emissions (subsidence reversal wetlands and rice agriculture). We estimate 0.1 to 0.2 MT CO_2 eq y^{-1} from these nine sub-habitats, under current extents and management strategies that contribute to the GHG footprint of Delta lands (2 to 3 MT CO_2 eq y^{-1}).

The three interventions (Figure 1) can reduce those Delta-wide positive emissions and thus improve the radiative balance, but not reverse it. The most effective actions to reduce radiative balance are those that raise water tables in

https://doi.org/10.15447/sfews.2023v20iss4art7

Table 1 Atmospheric GHG exchange by Intervention, Land Use Land Cover acreage, and future potential footprint (by 2060). (See also contributing data with uncertainty assessment in Appendix A, Table A1.)

Potential intervention (n=3)	Land use/Land cover (n=9)	Current hectares [a]	Potential hectares by 2060	CO_2 (g CO_2 m^{-2} y^{-1})	CH_4 (g CO_2 eq m^{-2} y^{-1})	N_2O (g CO_2 eq m^{-2} y^{-1}) [b]	Net footprint (g CO_2 eq m^{-2} y^{-1})	Current GHG footprint (1000xMg)	Potential 2060 GHG footprint (1000xMg)	Reference for GHG estimate
Status quo	Agriculture	165,000	165,000	2,050	neg	neg	2,050	338	338	Hemes et al. 2019; Bergamaschi et al. 2021
Ag Hydro Management	winter flooded	33,051	165,000	1,540	360	977	2,878	95	475	Hemes et al. 2019; Bergamaschi et al. 2021
Ag Hydro management	Rice	3,023	165,000	1,320	540	0	1,860	6	307	Hemes et al. 2019
Subsidence reversal	Permanently flooded wetland	1,092	12,424	-1,415	2,115	18	718	1	9	Hemes et al. 2019
Tidal reconnection	Seasonal wetland	12,439	12,439	1,122	405	0	1,527	19	19	assume pasture; Hemes et al. 2019
Tidal Maintenance	Tidal Marsh Brackish	3,517	7,000	-1,052	41	0	-1,011	-4	-7	Windham–Myers & Oikawa; Second State of Carbon Cycle Report (SOCCR2)default
Tidal Maintenance	Tidal Marsh Fresh	3,759	41,789	-1,236	2,115	0	879	3	37	Krauss et al. 2016; Louisiana (wide range)
Tidal Maintenance	Riparian Forest	7,933	35,903	-1,008	WR	0	-1,008	-9	-39	Wide range of CH_4; woody biomass only
Tidal Maintenance	Tidal Channel SAV	10,913	10,913	-367	225	0	-142	-2	-2	Drexler et al. 2021; river default CH_4
Tidal Maintenance	Tidal Channel FAV	723	723	-367	225	0	-142	0	0	Drexler et al. 2021; river default CH_4

a. Acreage values based on draft Delta Plan performance measures published May 2020, and from DPC (2020). These numbers have not been formally adopted.
b. Other non-included acreage categories from DSC 2020: Wet meadow/seasonal wetland: 17,115; Alkali Wetlands: 11,054; Non-tidal freshwater (this # includes some of the subsidence reversal projects): 5,931. CO_2eq conversions at 45x CH_4 (SGWP) and 298x N_2O. Limited data for N_2O. Wide Range (highly negative to highly positive) = WR. All intertidal and sub-tidal lands assume N_2O emissions are negligible (see Mitsch and Mander 2018; Krauss et al. 2016)

otherwise aerobic soils. By computing net GHG fluxes, immediate benefits would result from specific actions that alter operations in two regions: (1) halting CO_2 emissions through raising the water table on agricultural soils in the central Delta (e.g., growing rice with AWD), and (2) halting CH_4 emissions (and allowing C storage) through tidal reconnection in currently "freshened" seasonal wetlands of the Suisun Complex. Wetlands that reverse subsidence are not likely to result in a net negative radiative balance for 200+ years, but immediate benefits include reduced hydrostatic pressure on levee systems and a decreased radiative balance relative to the previous land use. As an example, for the 12,424 hectares of wetlands with reverse subsidence slated to be implemented on agricultural lands (Table 1), using the net footprint from Hemes et al. (2019) would result in an estimated net cooling effect of about 165,000 Mg or 1.3 kg CO_2–e m^{-2} y^{-1}

Current distributions of the nine sub-habitats are based on mapped estimates and tabular data. Future distributions are projected as potentials, and are highly dependent on if, when, and where these hydrologic interventions are applied. For example, if all seasonal wetlands (net positive) were breached to restore tidally refreshed wetlands, the immediate transition would be expected to reverse net emissions. At the Delta scale, this reversal could reduce the current landscape carbon footprint by 8% (from 2 MT to 1.85 MT CO_2 eq y^{-1}). Because of the extent and CO_2 fluxes of conventional and winter-flooded agriculture, a larger effect could result from alternative agricultural hydrologic management. For example, conversion to rice agriculture would improve radiative balance by up to ~36% (2,878 CO_2 eq $m^{-2} y^{-1}$ to 1860 CO_2 eq $m^{-2} y^{-1}$), with an additional ~30% improvement under AWD management. The uncertainties in the effect of these potential actions are directly proportional to future extents, whereby land decisions (levee repair, crop type, etc.) and climate forcings (SLR, salinity migration) determine the character of aquatic habitats. As such, a ranking of uncertainty is provided in Table 2. The ranking is primarily provided to characterize the net effect of each action on the Delta landscape, assuming basic landscape features are maintained (Figure 3). A framework for any climate mitigation actions on this Delta landscape will involve relative radiation balance assessments and their evolution through time, including their sustainability as ecosystems.

Future distributions and radiative balances are difficult to predict, but some general observations support the role of ocean-based influences leading to fewer emissions. Whereas global climate models predict oceans to become warmer and sea levels to rise at accelerated rates by 2100, ocean-based influences on terrestrial habitats are generally beneficial to C sequestration rates. Tidal waters have a cooling influence during flooded conditions that can reduce respiration rates, as well as reduce vapor- pressure-deficits (dry air) that reduce plant productivity (Knox et al. 2018). Further, tidal waters are a source of marine-based sulfate that can inhibit CH_4 production and emission through microbial inhibition (see Kroeger et al. 2017). Terrestrial-based effects of climate change include warmer air temperatures, less snowpack available for freshwater releases in summer, and increases in soil salinity through heightened evapotranspiration (Eichelman et al. 2022). These long-term drivers influence plant productivity more strongly than soil microbial activity and are incorporated in model feedbacks (Oikawa et al. 2017).

Further, future anthropogenic responses to climate and precipitation changes play a significant role in the potential for GHGs to be mitigated in the Delta. While landscape position and geomorphology control water levels, control of water flows (routing) through operations such as salinity gates, reservoir releases, levee maintenance, wastewater treatment, and cross-channel flows are dynamic adaptive responses to climate drivers, as are crop-management decisions and market responses. Projections of effects to soil carbon storage and net radiative balance from rising air temperatures and rising sea levels are more likely constrained by indirect operational responses than by direct climate predictors.

The rates we consider here are based on current measurements and systems, and the benefits of some actions will have a limited return as conditions change. In the larger context, this heavily managed Delta region has many constraints on the current system and future actions. These include concerns such as the cost of water supply, the susceptibility of actions to drought limitations, the growing local and global population that stimulates nutrient loading through agricultural intensity or wastewater, and the capacity of an action to generate a long-term benefit (e.g., resilience to SLR) (Kraus et al. 2017). Assumptions and projections considered with these actions have a much larger context in terms of implementation costs and stability under a future Delta landscape. Further, while Table 2 identifies specific data needs, based on current uncertainties, long-term monitoring is still required to quantify the climate-mitigation benefit of these actions. Confidence in current fluxes can point land managers toward likely beneficial actions, but our current data and tools are insufficient for dynamic future conditions

https://doi.org/10.15447/sfews.2023v20iss4art7

Table 2 Ranking of interventions and land use by acreage, impact, and uncertainty. Positions 1 through 9 are in order of data needs for constraining the radiative balance of interventions within this land-cover type.

Intervention class (n=3)	**Land-cover type**	**CURRENT acreage** (rank normalize on a scale of 1 to 9])	**FUTURE acreage** or potential % increase (rank)	**Delta-wide MT CO2 eq annual flux** (rank lowest to highest)	**Estimated net GHG emissions** (+ or -) see Table 1	**Uncertainty** (rank most uncertain = 9)	**Significant data needs for uncertainty**	**Overall rank for data needs** (avg score: CO2 eq and uncertainty)
Tidal connection	Fresh water tidal marsh	5	2	6	+	9	CH_4, lateral flux	1
Ag hydrology	Flooded ag	1	1	9	+	7	CH_4, lateral flux	2
Tidal connection	Seasonal wetland	2	3	7	+	8	CH_4, CO_2, lateral flux	3
Tidal connection	Riparian forest/ Floodplain	4	4	2	—	6	CH_4, CO_2, lateral flux	4
Ag hydrology	AWD rice	3	5	8	+	5	CH_4, lateral flux	5
Subsidence reversal	Permanently flooded wetland	6	6	5	+	1	Future extent	6
Tidal connection	Tidal channel (FAV)	7	7	4	—	4	CH_4, extent	7
Tidal connection	Tidal channel (SAV)	8	8	3	—	3	CH_4, extent	8
Tidal connection	Brackish/ saline tidal marsh	9	9	1	—	2	Future extent	9

given changing climate, landscape, and operational drivers.

CONCLUSION

Climate mitigation and adaptation opportunities through hydrologic management in Delta and Suisun Bay are profound, but projections are uncertain, given the multiple intersecting dynamics of Delta land use and land-cover (e.g., cultural, economic, tectonic, climatic, and biological drivers). Despite the region's globally significant soil carbon stocks and future carbon mitigation potential, the three primary interventions described here—agricultural hydrologic management, impoundment for subsidence reversal, and tidal reconnectivity—are only partially effective in sustaining and restoring aquatic habitats for their carbon-related ecosystem services. Given the dominance of agricultural land on the Delta's carbon footprint, carbon sequestration and GHG mitigation actions on non-agricultural lands could potentially reduce radiative balances by around 10%. Thus, the baseline and future sustainability of the climate-mitigating interventions examined here are very sensitive to anthropogenic and non-anthropogenic drivers. We note that climate mitigation is incremental and need not reverse a site from source to sink; *any* actions that reduce emissions mitigate GHGs. The long history of soil core data shows adaptive responses to environmental changes, and carbon densities in cores are high (mean = $0.04\,g\ C\ cm^{-3}$), even during periods of rapid change. The consistency of this deep stock accumulation, even under changing conditions, provides confidence that tidal connectivity can restart carbon accretion in soil.

Among the habitats reviewed, agriculture is currently the single largest producer of CO_2 fluxes and thus GHG emissions, even with winter flooding incorporated. The agricultural influence is dominated by the oxidative loss of soil C and thus elevation loss (subsidence). However, interventions can mitigate and reduce this strongly positive radiative balance. Models can help anticipate the effect of these interventions, providing insight into net C exchanges and CH_4 emissions as elevations change and vegetation communities are altered by active and passive responses. However, extensive monitoring is needed to validate models and to develop new estimates for the Delta's freshwater tidal wetlands. While CO_2 fluxes can be modeled to some degree across Delta habitats (Oikawa et al. 2017), large uncertainties remain in current CH_4 and N_2O fluxes, as well as in potential changes in acreage. Some outstanding uncertainties and data gaps are evident in freshwater tidal and SAV and FAV habitats, which are likely to expand dramatically through EcoRestore program objectives. Extreme events could alter the future scenarios estimated here, but we predict that transformation from a highly channelized and engineered binary landscape to a more open tidal system (marsh, floodplain) would protect historical soil C storage, increase soil C sequestration, and reduce CH_4 emissions. Actions focused on current agriculture—including restoration of historical peatlands through impounded wetlands and agricultural flooding—can reduce soil oxidation and provide a means for reaching open tidal elevations.

ACKNOWLEDGEMENTS

We recognize the contributions of multiple scientists, and reviewers within the Delta Science Program, for the data and editing that improved the manuscript. We also benefitted from targeted review comments of Brian Bergamaschi (US Geological Survey).

REFERENCES

Abernethy S, Jackson RB. 2022. Global temperature goals should determine the time horizons for greenhouse gas emission metrics. Env Res Lett. [accessed 2022 Oct 07];17(2):024019 *https://iopscience.iop.org/article/10.1088/1748-9326/ac4940/meta*

Alpers CN, Fleck JA, Marvin–DiPasquale M, Stricker CA, Stephenson M, Taylor HE. 2014. Mercury cycling in agricultural and managed wetlands, Yolo Bypass, California: spatial and seasonal variations in water quality. Sci Tot Env. [accessed 2022 Oct 07];484:276–287. *https://doi.org/10.1016/j.scitotenv.2013.10.096*

Anderson FE, Bergamaschi BA, Sturtevant C, Knox S, Hastings L, Windham–Myers L, Detto M, Hestir EL, Drexler JZ, Miller RL, et al. 2016. Variation of energy and carbon fluxes from a restored temperate freshwater wetland and implications for carbon market verification protocols. JGR: Biogeosci. [accessed 2022 Oct 07];121(3):777–795. *https://doi.org/10.1002/2015JG003083*

Anthony TL, Silver WL. 2021. Hot moments drive extreme nitrous oxide and methane emissions from agricultural peatlands. Glob Change Biol. [accessed 2022 Oct 07];27(20):5141–5153. *https://doi.org/10.1111/gcb.15802*

Arias–Ortiz A, Oikawa PY, Carlin J, Masqué P, Shahan J, Kanneg S, Paytan A, Baldocchi DD. 2021. Tidal and nontidal marsh restoration: a trade-off between carbon sequestration, methane emissions, and soil accretion. JGR: Biogeosci. [accessed 2022 Oct 07];e2021JG006573. *https://doi.org/10.1029/2021JG006573*

Atwater B.F. 1982. Geologic maps of the Sacramento–San Joaquin Delta, California. Washington (DC): US Government Printing Office. USGS Report No. 1401). [accessed 2022 Oct 07]. 15 p., 21 sheets. *https://doi.org/10.3133/mf1401*

Baker SE, Stolaroff JK, Peridas G, Pang SH, Goldstein HM, Lucci FR, Li W, Slessarev EW, Pett-Ridge J, Ryerson FJ, et al. 2020. Getting to neutral: options for negative carbon emissions in California. Lawrence Livermore National Laboratory, LLNL-TR-796100. [accessed 2022 Oct 07]. Available from: *https://gs.llnl.gov/sites/gs/files/2021-08/getting_to_neutral.pdf*

Bates ME, Lund JR. 2013. Delta subsidence reversal, levee failure, and aquatic habitat—a cautionary tale. San Fran Estuary Watershed Sci. [accessed 2022 Oct 07];11(1). *https://doi.org/10.15447/sfews.2013v11iss1art1*

Bergamaschi BA, Anderson FE, Stuart-Haëntjens EJ, Pellerin BA. 2021. Winter flooding to conserve agricultural peat soils in a temperate climate: effect on greenhouse gas emissions and global warming potential. In: Krauss KW, Zhu Z, Stagg CL, editors. Wetland carbon and environmental management. Chapter 17 In: AGU Geophysical Monograph Series. [accessed 2022 Oct 07];321–337. *https://doi.org/10.1002/9781119639305.ch17*

Bianchi TS, Allison MA. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proc Natl Acad Sci. [accessed 2022 Oct 07];106(20):8085–8092. *https://doi.org/10.1073/pnas.0812878106*

Bianchi TS, Cui X, Blair NE, Burdige DJ, Eglinton TI, Galy V. 2018. Centers of organic carbon burial and oxidation at the land-ocean interface. Org Geochem. [accessed 2022 Oct 07];115:138–155. *https://doi.org/10.1016/j.orggeochem.2017.09.008*

Bogard MJ, Bergamaschi BA, Butman DE, Anderson FE, Knox SH, Windham–Myers L. 2020. Hydrologic export is a major component of coastal wetland carbon budgets. Glob Biogeochem Cycles. [accessed 2022 Oct 07];34(8):e2019GB006430. *https://doi.org/10.1029/2019GB006430*

Boyer K, Safran SM, Khanna S, Patten MV. 2023. Landscape transformation and variation in invasive species abundance drive change in primary production of aquatic vegetation in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci 20(4). *https://doi.org/10.15447/sfews.2023v20iss4art2*

Bridgham SD, Pastor J, Dewey B, Weltzin JF, Updegraff K. 2008. Rapid carbon response of peatlands to climate change. Ecology. [accessed 2022 Oct 07];89(11):3041–3048. *https://doi.org/10.1890/08-0279.1*

Bridgham SD, Megonigal JP, Keller JK, Bliss NB, Trettin C. 2006. The carbon balance of North American wetlands. Wetlands. [accessed 2022 Oct 07];26(4):889-916. *https://doi.org/10.1672/0277-5212(2006)26[889:TCBONA]2.0.CO;2*

Burgin AJ, Lazar JG, Groffman PM, Gold AJ, and Kellogg DQ. 2013. Balancing nitrogen retention ecosystem services and greenhouse gas disservices at the landscape scale. Ecol Engin. [accessed 2022 Oct 07];56:26–35. *https://doi.org/10.1016/j.ecoleng.2012.05.003*

Byrd KB, Ballanti L, Thomas N, Nguyen D, Holmquist JR, Simard M, Windham–Myers L. 2018. A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS J Photogramm Remote Sens. [accessed 2022 Oct 07];139:255–271. *https://doi.org/10.1016/j.isprsjprs.2018.03.019*

Byrd KB, Windham–Myers L, Leeuw T, Downing B, Morris JT, Ferner MC. 2016. Forecasting tidal marsh elevation and habitat change through fusion of Earth observations and a process model. Ecosphere. [accessed 2022 Oct 07];7(11):e01582. *https://doi.org/10.1002/ecs2.1582*

Callaway JC, Borgnis EL, Turner RE, Milan CS. 2012. Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries Coasts. [accessed 2022 Oct 07];35(5):1163–1181. *https://doi.org/10.1007/s12237-012-9508-9*

Callaway JC. 2018. Accretion: measurement and interpretation of wetland sediments. In: Windham–Myers L, Crooks S, Troxler TG, editors. A blue carbon primer. p. 81-92. Boca Raton (FL): CRC Press.

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G. 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc Nat Acad Sci. [accessed 2022 Oct 07];104(47):18866–18870. *https://doi.org/10.1073/pnas.0702737104*

Cloern JE. 2019. Patterns, pace, and processes of water-quality variability in a long-studied estuary. Limnol Oceanogr [accessed 2022 Oct 07];64(S1):S192–S208. *https://doi.org/10.1002/lno.10958*

Cloern JE, Safran SM, Vaughn LS, Robinson A, Whipple AA, Boyer KE, Drexler JZ, Naiman RJ, Pinckney JL, Howe ER, Canuel EA. 2021. On the human appropriation of wetland primary production. Sci Tot Environ. [accessed 2022 Oct 07];785:147097. *https://doi.org/10.1016/j.scitotenv.2021.147097*

Conrad JL, Madison T, Jetter K, Madsen J, Pratt P, Moran P, Takekawa J, Skurka Darin G, Lydia Kenison L. 2023. Invasive aquatic vegetation in the Sacramento–San Joaquin Delta and Suisun Marsh: the history and science of control efforts and recommendations for the path forward. San Franc Estuary Watershed Sci. 20(4). *https://doi.org/10.15447/sfews.2023v20iss4art4*

Damashek J, Smith JM, Mosier AC, Francis CA. 2015. Benthic ammonia oxidizers differ in community structure and biogeochemical potential across a riverine delta. Front Microbiol. [accessed 2022 Oct 07];5:743. *https://doi.org/10.3389/fmicb.2014.00743*

Deegan LA, Johnson DS, Warren RS, Peterson BJ, Fleeger JW, Fagherazzi S, Wollheim WM. 2012. Coastal eutrophication as a driver of salt marsh loss. Nature. [accessed 2022 Oct 07]:490(7420):388–392 *https://doi.org/10.1038/nature11533*

[DSC] Delta Stewardship Council. 2020. Delta adapts: creating a climate resilient future. sacramento-san joaquin delta climate change vulnerability assessment. Sacramento-San Joaquin River Delta climate change vulnerability assessment Draft economic impact and exposure analysis technical memo. [accessed 2022 Oct 07] Available from: *https://www.deltacouncil.ca.gov/pdf/delta-plan/2021-01-15-delta-adapts-economic-assessment.pdf*

[DPC] Delta Protection Council. 2020. The state of Delta agriculture: economic impact, conservation and trends. [accessed 2022 Oct 07]. Available from: *https://delta.ca.gov/wp-content/uploads/2020/07/Ag-ESP-update-agricultural-trends-FINAL-508.pdf*

Deverel SJ, Dore S, Schmutte C. 2020. Solutions for subsidence in the California Delta, USA, an extreme example of organic-soil drainage gone awry. Proc Int Assoc Hydrol Sci. [accessed 2022 Oct 07];382:837–842. *https://doi.org/10.5194/piahs-382-837-2020*

Deverel S, Jacobs P, Lucero C, Dore S, Kelsey TR. 2017. Implications for greenhouse gas emission reductions and economics of a changing agricultural mosaic in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2022 Oct 07] 15(3). *https://doi.org/10.15447/sfews.2017v15iss3art2*

Deverel SJ, Leighton DA. 2010. Historic, recent, and future subsidence, Sacramento–San Joaquin Delta, California, USA. San Franc Estuary Watershed Sci. [accessed 2022 Oct 07];8(2). *https://doi.org/10.15447/sfews.2010v8iss2art1*

Deverel SJ, Ingrum T, Leighton D. 2016. Present-day oxidative subsidence of organic soils and mitigation in the Sacramento–San Joaquin Delta, California, USA. Hydrogeol J. [accessed 2022 Oct 07];24(3):569–586. *https://doi.org/10.1007/s10040-016-1391-1*

Deverel SJ, Leighton DA, Lucero C, Ingrum T. 2017. Simulation of subsidence mitigation effects on island drain flow, seepage, and organic carbon loads on subsided islands Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2022 Oct 07];15(4). *https://doi.org/10.15447/sfews.2017v15iss4art2*

Deverel SJ, Lucero CE, Bachand S. 2015. Evolution of arability and land use, Sacramento–San Joaquin Delta, California. San Franc Estuary Watershed Sci. [accessed 2022 Oct 07];13(2). *https://doi.org/10.15447/sfews.2015v13iss2art4*

Drexler JZ. 2011. Peat formation processes through the millennia in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries Coasts. [accessed 2022 Oct 07];34:900–911. *https://doi.org/10.1007/s12237-011-9393-7*

Drexler JZ, Alpers CN, Neymark LA, Paces JB, Taylor HE, Fuller CC. 2016. A millennial-scale record of Pb and Hg contamination in peatlands of the Sacramento–San Joaquin Delta of California, USA. Sci Tot Environ. [accessed 2022 Oct 07];551–552:738–751. *https://doi.org/10.1016/j.scitotenv.2016.01.201*

Drexler JZ, de Fontaine CS, Brown TA. 2009a. Peat accretion histories during the past 6,000 years in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries Coasts. [accessed 2022 Oct 07];32(5):871–892. *https://doi.org/10.1007/s12237-009-9202-8*

Drexler JZ, de Fontaine CS, Deverel SJ. 2009b. The legacy of wetland drainage on the remaining peat in the Sacramento–San Joaquin Delta, California, USA. Wetlands. [accessed 2022 Oct 07];29:372–386. *https://doi.org/10.1672/08-97.1*

Drexler JZ, Khanna S, Lacy J. 2021. Carbon storage and sediment trapping by *Egeria densa* Planch., a globally invasive, freshwater macrophyte. Sci Total Environ. [accessed 2022 Oct 07];755(1):142602. *https://doi.org/10.1016/j.scitotenv.2020.142602*

Drexler JZ, Khanna S, Schoellhamer DH, Orlando J. 2019. The fate of blue carbon in the Sacramento–San Joaquin Delta of California, USA. In: Windham–Myers L, Crooks S, Troxler TG, editors. A blue carbon primer: the state of coastal wetland carbon science, practice, and policy. Boca Raton (FL): CRC Press. 550 p.

Drexler JZ, Paces J, Alpers CN, Windham–Myers L, Neymark L, Taylor HE. 2013a. $^{234}U/^{238}U$ and 87Sr in peat as useful tracers of paleosalinity in the Sacramento-San Joaquin Delta of California. Appl Geochem. [accessed 2022 Oct 07];40:164-179. *https://www.sciencedirect.com/science/article/abs/pii/S088329271300262X*

Drexler JZ, Krauss KW, Sasser MC, Fuller CC, Swarzenski CM, Powell A, Swanson KM, Orlando J. 2013b. A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. Wetlands. [accessed October 2022];33(5):965–974. *https://doi.org/10.1007/s13157-013-0456-3*

Dybala KE, Matzek V, Gardali T, Seavy NE. 2019. Carbon sequestration in riparian forests: a global synthesis and meta-analysis. Glob Change Biol. [accessed 2022 Oct 07];25(1):57–67. *https://doi.org/10.1111/gcb.14475*

Eichelmann E, Mantoani MC, Chamberlain SD, Hemes KS, Oikawa PY, Szutu D, Valach A, Verfaillie J, Baldocchi DD. 2022. A novel approach to partitioning evapotranspiration into evaporation and transpiration in flooded ecosystems. Glob Change Biol. [accessed 2022 Oct 07];28(3):990–1007. *https://doi.org/10.1111/gcb.15974*

Fard E, Brown LN, Lydon S, Smol JP, MacDonald GM. 2021. High-resolution sedimentological and geochemical records of three marshes in San Francisco Bay, California. Quatern Intl. [accessed 2022 Oct 07];602:49–65. *https://doi.org/10.1016/j.quaint.2021.05.002*

Fargione JE, Bassett S, Boucher T, Bridgham SD, Conant RT, Cook-Patton SC, Ellis PW, Falcucci A, Fourqurean JW, Gopalakrishna T, Gu H. 2018. Natural climate solutions for the United States. Science Advances. [accessed 2022 Oct 07];4(11):eaat1869. *https://www.science.org/doi/10.1126/sciadv.aat1869*

Fertitta–Roberts C, Oikawa PY, Jenerette GD. 2019. Evaluating the GHG mitigation-potential of alternate wetting and drying in rice through life cycle assessment. Sci Total Environ. [accessed 2022 Oct 07];653:1343–1353. *https://doi.org/10.1016/j.scitotenv.2018.10.327*

Galloway DL, Jones DR, Ingebritsen SE. 2000. Land subsidence in the United States. (Vol. 1182). USGS Fact Sheet 165-00. [accessed 2022 Oct 07]. Available from: *https://water.usgs.gov/ogw/pubs/fs00165/*

Goman M, Wells L. 2000. Trends in river flow affecting the northeastern reach of the San Francisco Bay estuary over the past 7000 years. Quatern Res. [accessed 2022 Oct 07];54(2):206–217. *https://doi.org/10.1006/qres.2000.2165*

Graves RA, Haugo RD, Holz A, Nielsen–Pincus M, Jones A, Kellogg B, Macdonald C, Popper K, Schindel M. 2020. Potential greenhouse gas reductions from natural climate solutions in Oregon, USA. PLoS ONE. [accessed 2022 Oct 07];15(4):e0230424. *https://doi.org/10.1371/journal.pone.0230424*

Groffman PM, Butterbach–Bahl K, Fulweiler RW, Gold AJ, Morse JL, Stander EK, Tague C, Tonitto C, Vidon P. 2009. Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models. Biogeochem. [accessed 2022 Oct 07];93(1):49–77. *https://doi.org/10.1007/s10533-008-9277-5*

Günther A, Barthelmes A, Huth V, Joosten H, Jurasinski G, Koebsch F, Couwenberg J. 2020. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat Comm. [accessed 2022 Oct 07];11(1):1–5. *https://doi.org/10.1038/s41467-020-15499-z*

Hatala JA, Detto M, Sonnentag O, Deverel SJ, Verfaillie J, Baldocchi DD. 2012. Greenhouse gas (CO_2, CH_4, H_2O) fluxes from drained and flooded agricultural peatlands in the Sacramento–San Joaquin Delta. Agr Ecosyst Environ. [accessed 2022 Oct 07] 150, pp.1–18. *https://doi.org/10.1016/j.agee.2012.01.009*

Hemes KS, Chamberlain SD, Eichelmann E, Knox SH, Baldocchi DD. 2018. A biogeochemical compromise: the high methane cost of sequestering carbon in restored wetlands. Geophys Res Lett. 45(12):6081–6091. *https://doi.org/10.1029/2018GL077747*

Hemes KS, Chamberlain SD, Eichelmann E, Anthony T, Valach A, Kasak K, Szutu D, Verfaillie J, Silver WL, Baldocchi DD. 2019. Assessing the carbon and climate benefit of restoring degraded agricultural peat soils to managed wetlands. Agr Forest Meteorol. [accessed 2022 Oct 07];268:202–214. *https://doi.org/10.1016/j.agrformet.2019.01.017*

Herbert ER, Windham–Myers L, Kirwan ML. 2021. Sea-level rise enhances carbon accumulation in United States tidal wetlands. One Earth. [accessed 2022 Oct 07];4(3):425–433. *https://doi.org/10.1016/j.oneear.2021.02.011*

Holmquist JR, Windham–Myers L, Bernal B, Byrd KB, Crooks S, Gonneea ME, Herold N, Knox SH, Kroeger KD, McCombs J, Megonigal JP. 2018a. Uncertainty in United States coastal wetland greenhouse gas inventorying. Environ Res Lett. [accessed 2022 Oct 07];13(11):115005. Available from: *https://iopscience.iop.org/article/10.1088/1748-9326/aae157/meta*

Holmquist JR, Windham–Myers L, Bliss N, Crooks S, Morris JT, Megonigal JP, Troxler T, Weller D, Callaway J, Drexler J, Ferner MC et al. 2018b. Accuracy and precision of tidal wetland soil carbon mapping in the conterminous United States. Sci Rep. [accessed 2022 Oct 07];8(1):1–16. *https://doi.org/10.1038/s41598-018-26948-7*

Huang Y, Ciais P, Luo Y, Zhu D, Wang Y, Qiu C, Goll DS, Guenet B, Makowski D, De Graaf I, et al. 2021. Tradeoff of CO_2 and CH_4 emissions from global peatlands under water-table drawdown. Nat Clim Change. [accessed 2022 Oct 07];11(7):618–22. *https://doi.org/10.1038/s41558-021-01059-w*

[IPCC] International Panel on Climate Change. 2014. 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M, Troxler, TG, editors. Switzerland: IPCC. Available from: *https://www.ipcc.ch/site/assets/uploads/2018/03/Wetlands_Supplement_Entire_Report.pdf*

Ingebritsen SE, Ikehara ME, Galloway DL, Jones DR. 2000. Delta subsidence in California: the sinking heart of the state. US Department of the Interior, USGS Fact Sheet 005-00. [accessed 2022 Oct 07] *https://pubs.usgs.gov/fs/2000/fs00500/*

Kirwan ML, Megonigal JP. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature. 504(7478):53–60. *https://doi.org/10.1038/nature12856*

Knox SH, Sturtevant C, Matthes JH, Koteen L, Verfaillie J, Baldocchi DD. 2015. Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO_2 and CH_4) fluxes in the Sacramento–San Joaquin Delta. Glob Change Biol. [accessed 2022 Oct 07];21(2):750–765. *https://doi.org/10.1111/gcb.12745*

Knox SH, Windham–Myers L, Anderson F, Sturtevant C, Bergamaschi B. 2018. Direct and indirect effects of tides on ecosystem-scale CO_2 exchange in a brackish tidal marsh in Northern California. J Geophys Res: Biogeosci. [accessed 2022 Oct 07];123(3):787–806. *https://doi.org/10.1002/2017JG004048*

Knox SH, Bansal S, McNicol G, Schafer K, Sturtevant C, Ueyama M, Valach AC, Baldocchi D, Delwiche K, Desai AR, Euskirchen E. 2021. Identifying dominant environmental predictors of freshwater wetland methane fluxes across diurnal to seasonal time scales. Global Change Biol. [accessed 2022 Oct 07];27(15):3582-3604. *https://doi.org/10.1111/gcb.15661*

Kraus TE, O'Donnell K, Downing BD, Burau JR, Bergamaschi BA. 2017. Using paired in situ high frequency nitrate measurements to better understand controls on nitrate concentrations and estimate nitrification rates in a wastewater-impacted river. Water Resour Res. [accessed 2022 Oct 07];53(10):8423–8442. *https://doi.org/10.1002/2017WR020670*

Krauss KW, Holm Jr GO, Perez BC, McWhorter DE, Cormier N, Moss RF, Johnson DJ, Neubauer SC, Raynie RC. 2016. Component greenhouse gas fluxes and radiative balance from two deltaic marshes in Louisiana: pairing chamber techniques and eddy covariance. J Geophys Res: Biogeosci. [accessed 2022 Oct 07];121(6):1503–1521. *https://doi.org/10.1002/2015JG003224*

Kroeger KD, Crooks S, Moseman–Valtierra S, Tang J. 2017. Restoring tides to reduce methane emissions in impounded wetlands: a new and potent Blue Carbon climate change intervention. Sci Rep. [accessed 2022 Oct 07];7(1):1–12. *https://doi.org/10.1038/s41598-017-12138-4*

Loisel J, Gallego–Sala AV, Amesbury MJ, Magnan G, Anshari G, Beilman DW, Benavides JC, Blewett J, Camill P, Charman DJ, et al. 2021. Expert assessment of future vulnerability of the global peatland carbon sink. Nat Clim Change. [accessed 2022 Oct 07];11(1):70–77. *https://doi.org/10.1038/s41558-020-00944-0*

Loisel J, Yu Z, Beilman DW, Camill P, Alm J, Amesbury MJ, Anderson D, Andersson S, Bochicchio C, Barber K, Belyea LR et al. 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. Holocene. [accessed 2022 Oct 07];24(9):1028–1042. *https://doi.org/10.1177/0959683614538073*

Loucks DP. 2019. Developed river deltas: are they sustainable? Environ Res Lett. [accessed 2022 Oct 07];14(11):113004. Available from: *https://iopscience.iop.org/article/10.1088/1748-9326/ab4165/meta*

Madani K, Lund JR. 2012. California's Sacramento–San Joaquin delta conflict: from cooperation to chicken. J Water Resour Plan Manag. [accessed 2022 Oct 07];138(2):90–99. Available from: *https://ascelibrary.org/doi/10.1061/%28ASCE%29WR.1943-5452.0000164*

Malamud–Roam FP, Ingram BL, Hughes M, Florsheim JL. 2006. Holocene paleoclimate records from a large California estuarine system and its watershed region: linking watershed climate and bay conditions. Quatern Sci Rev. [accessed 2022 Oct 07];25(13–14):1570–1598. *https://doi.org/10.1016/j.quascirev.2005.11.012*

Martin RM, Wigand C, Elmstrom E, Lloret J, Valiela I. 2018. Long-term nutrient addition increases respiration and nitrous oxide emissions in a New England salt marsh. Ecol Evol. [accessed 2022 Oct 07];8(10):4958–4966. *https://doi.org/10.1002/ece3.3955*

Marvin–DiPasquale M, Windham–Myers L, Agee JL, Kakouros E, Kieu LH, Fleck JA, Alpers CN, Stricker CA. 2014. Methylmercury production in sediment from agricultural and non-agricultural wetlands in the Yolo Bypass, California, USA. Sci Total Environ. [accessed 2022 Oct 07];484:288–299. *https://doi.org/10.1016/j.scitotenv.2013.09.098*

Matzek V, Stella J, Ropion P. 2018. Development of a carbon calculator tool for riparian forest restoration. Appl Veget Sci. [accessed 2022 Oct 07];21(4):584–594. *https://doi.org/10.1111/avsc.12400*

McNicol G, Sturtevant CS, Knox SH, Dronova I, Baldocchi DD, Silver WL. 2017. Effects of seasonality, transport pathway, and spatial structure on greenhouse gas fluxes in a restored wetland. Global Change Biol. [accessed 2022 Oct 07];23(7):2768–2782. *https://doi.org/10.1111/gcb.13580*

Miller RL, Fram M, Fujii R, Wheeler G. 2008. Subsidence reversal in a re-established wetland in the Sacramento–San Joaquin Delta, California, USA. San Franc Estuary Watershed Sci. [accessed 2022 Oct 07];6(3). *https://doi.org/10.15447/sfews.2008v6iss3art1*

Miller RL. 2011. Carbon gas fluxes in re-established wetlands on organic soils differ relative to plant community and hydrology. Wetlands [accessed 2022 Oct 07];31(6):1055–1066. *https://doi.org/10.1007/s13157-011-0215-2*

Mitsch WJ, Mander Ü. 2018. Wetlands and carbon revisited. Ecol Engineer. [accessed 2022 Oct 07];114:1–6. *https://doi.org/10.1016/j.ecoleng.2017.12.027*

Moomaw WR, Chmura GL, Davies GT, Finlayson CM, Middleton BA, Natali SM, Perry, JE, Roulet N, Sutton–Grier AE. 2018. Wetlands in a changing climate: science, policy and management. Wetlands. [accessed 2022 Oct 07];38(2):183–205. *https://doi.org/10.1007/s13157-018-1023-8*

Morin TH, Bohrer G, Stefanik KC, Rey–Sanchez AC, Matheny AM, Mitsch WJ. 2017. Combining eddy-covariance and chamber measurements to determine the methane budget from a small, heterogeneous urban floodplain wetland park. Agr Forest Meteorol. [accessed 2022 Oct 07];237:160–170. *https://doi.org/10.1016/j.agrformet.2017.01.022*

Morris JT, Barber DC, Callaway JC, Chambers R, Hagen SC, Hopkinson CS, Johnson BJ, Megonigal P, Neubauer SC, Troxler T, et al. 2016. Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. Earth's Future. [accessed 2022 Oct 07];4(4):110–121. *https://doi.org/10.1002/2015EF000334*

Moseman–Valtierra S, Gonzalez R, Kroeger KD, Tang J, Chao WC, Crusius J, Bratton J, Green A, Shelton J. 2011. Short-term nitrogen additions can shift a coastal wetland from a sink to a source of N_2O. Atmos Environ. [accessed 2022 Oct 07];45(26):4390–4397. *https://doi.org/10.1016/j.atmosenv.2011.05.046*

Mount J, Twiss R. 2005. Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2022 Oct 07];3(1). *https://doi.org/10.15447/sfews.2005v3iss1art7*

Moyle PB, Brown LR, Durand JR, Hobbs JA. 2016. Delta Smelt: life history and decline of a once-abundant species in the San Francisco Estuary. San Franc Estuary Watershed Sci. [accessed 2022 Oct 07];14(2). *https://doi.org/10.15447/sfews.2016v14iss2art6*

Mozdzer TJ, Zieman JC, McGlathery KJ. 2010. Nitrogen uptake by native and invasive temperate coastal macrophytes: importance of dissolved organic nitrogen. Estuaries Coasts. [accessed 2022 Oct 07];33(3):784–797. *https://doi.org/10.1007/s12237-009-9254-9*

[NASEM] National Academies of Sciences, Engineering, and Medicine. 2019. Negative emissions technologies and reliable sequestration: a research agenda. Washington (DC): The National Academies Press. p. 550. *https://doi.org/10.17226/25259*

Neubauer SC. 2021. Global warming potential Is not an ecosystem property. Ecosystems. [accessed 2022 Oct 07];24:2079–2089. *https://doi.org/10.1007/s10021-021-00631-x*

Oikawa PY, Jenerette GD, Knox SH, Sturtevant C, Verfaillie J, Dronova I, Poindexter CM, Eichelmann E, Baldocchi DD. 2017. Evaluation of a hierarchy of models reveals importance of substrate limitation for predicting carbon dioxide and methane exchange in restored wetlands. J Geophys Res: Biogeosci [accessed 2022 Oct 07];122(1):145–167. *https://doi.org/10.1002/2016JG003438*

Page SE, Baird, AJ. 2016. Peatlands and global change: response and resilience. Ann Rev Environ Resour. [accessed 2022 Oct 07];41:35–57. *https://doi.org/10.1146/annurev-environ-110615-085520*

Pendleton L, Donato DC, Murray BC, Crooks S, Jenkins WA, Sifleet S, Craft C, Fourqurean JW, Kauffman JB, Marbà N, et al. 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS ONE. [accessed 2022 Oct 07];7(9):e43542 *https://doi.org/10.1371/journal.pone.0043542*

Poffenbarger HJ, Needelman BA, Megonigal JP. 2011. Salinity influence on methane emissions from tidal marshes. Wetlands. [accessed 2022 Oct 07];31(5):831–842. *https://doi.org/10.1007/s13157-011-0197-0*

Poulter B, Fluet–Chouinard E, Hugelius G, Koven C, Fatoyinbo L, Page SE, Rosentreter JA, Smart LS, Taillie PJ, Thomas N, Zhang Z. 2021. A review of global wetland carbon stocks and management challenges. Chapter 1 In: Krauss KW, Zhu Z, Stagg CL, editors. Wetland carbon and environmental management. [accessed 2022 Oct 07];1–20. *https://doi.org/10.1002/9781119639305.ch1*

Richardson CM, Fackrell JK, Kraus TE, Young MB, Paytan A. 2020. Lateral carbon exports from drained peatlands: an understudied carbon pathway in the Sacramento–San Joaquin Delta, California. J Geophys Res: Biogeosci. [accessed 2022 Oct 07];125(12):1–21. *https://doi.org/10.1029/2020JG005883*

Rogers K, Kelleway JJ, Saintilan N, Megonigal JP, Adams JB, Holmquist JR, Lu M, Schile–Beers L, Zawadzki A, Mazumder D, et al. 2019. Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature. [accessed 2022 Oct 07];567(7746):91–95. *https://doi.org/10.1038/s41586-019-0951-7*

Rosentreter JA, Borges AV, Deemer BR, Holgerson MA, Liu S, Song C, Melack J, Raymond PA, Duarte CM, Allen GH, Olefeldt D. 2021. Half of global methane emissions come from highly variable aquatic ecosystem sources. Nat Geosci. [accessed 2022 Oct 07];14(4):225–230. *https://doi.org/10.1038/s41561-021-00715-2*

Runkle BR, Suvočarev K, Reba ML, Reavis CW, Smith SF, Chiu YL, Fong B. 2018. Methane emission reductions from the alternate wetting and drying of rice fields detected using the eddy covariance method. Environ Sci Technol. [accessed 2022 Oct 07];53(2):671–681. *https://doi.org/10.1021/acs.est.8b05535*

Santos IR, Burdige DJ, Jennerjahn TC, Bouillon S, Cabral A, Serrano O, Wernberg T, Filbee–Dexter K, Guimond JA, Tamborski JJ. 2021. The renaissance of Odum's outwelling hypothesis in 'Blue Carbon' science. Estuarine Coastal Shelf Sci. [accessed 2022 Oct 07];255:107361. *https://doi.org/10.1016/j.ecss.2021.107361*

Saunois M, Bousquet P, Poulter B, Peregon A, Ciais P, Canadell JG, Dlugokencky EJ, Etiope G, Bastviken D, Houweling S, et al. 2016. The global methane budget 2000–2012. Earth Syst Sci Data. [accessed 2022 Oct 07];8(2):697–751. *https://doi.org/10.5194/essd-8-697-2016*

Schile LM, Callaway JC, Morris JT, Stralberg D, Parker VT, Kelly M. 2014. Modeling tidal marsh distribution with sea-level rise: evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency. PLoS ONE. [accessed 2022 Oct 07];9(2):e88760. *https://doi.org/10.1371/journal.pone.0088760*

Simmonds MB, Anders M, Adviento–Borbe MA, van Kessel C, McClung A, Linquist BA. 2015. Seasonal methane and nitrous oxide emissions of several rice cultivars in direct-seeded systems. J EnvironQuality. [accessed 2022 Oct 07];44(1):103–114. *https://doi.org/10.2134/jeq2014.07.0286*

Spivak AC, Sanderman J, Bowen JL, Canuel EA, Hopkinson CS. 2019. Global-change controls on soil-carbon accumulation and loss in coastal vegetated ecosystems. Nature Geosci. [accessed 2022 Oct 07];12(9):685–692. *https://doi.org/10.1038/s41561-019-0435-2*

Stern D, Chapple D, Copeland C. 2022. The dangerous disappearance of Delta dirt. Front Young Minds. [accessed 2022 Oct 07]. *https://doi.org/10.3389/frym.2022.613190*

Stralberg D, Brennan M, Callaway JC, Wood JK, Schile LM, Jongsomjit D, Kelly M, Parker VT, Crooks S. 2011. Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. PLoS ONE. [accessed 2022 Oct 07];6(11):e27388. *https://doi.org/10.1371/journal.pone.0027388*

Sutton–Grier AE, Moore A. 2016. Leveraging carbon services of coastal ecosystems for habitat protection and restoration. Coastal Manag. [accessed 2022 Oct 07];44(3):259–277 *https://doi.org/10.1080/08920753.2016.1160206*

Swanson KM, Drexler JZ, Schoellhamer DH, Thorne KM, Casazza ML, Overton CT, Callaway JC, Takekawa JY. 2014. Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco estuary. Estuaries Coasts. [accessed 2022 Oct 07];37(2):476–492. *https://doi.org/10.1007/s12237-013-9694-0*

Tanner KC, Windham–Myers L, Marvin–DiPasquale MC, Fleck JA, Linquist BA. 2018. Alternate wetting and drying decreases methylmercury in flooded rice (*Oryza sativa*) systems. Soil Sci Soc Am J. [accessed 2022 Oct 07];82(1):115–125. *https://doi.org/10.2136/sssaj2017.05.0158*

Thorne K, MacDonald G, Guntenspergen G, Ambrose R, Buffington K, Dugger B, Freeman C, Janousek C, Brown L, Rosencranz J, Holmquist J. 2018. US Pacific coastal wetland resilience and vulnerability to sea-level rise. Sci Advances. [accessed 2022 Oct 07];4(2):p.eaao3270. Available from: *https://www.science.org/doi/full/10.1126/sciadv.aao3270*

[USGCRP] U.S. Global Change Research Program. 2018: Second state of the carbon cycle report (SOCCR2): A sustained assessment report. Cavallaro N, Shrestha G, Birdsey R, Mayes MA, Najjar RG, Reed SC, Romero-Lankao, Zhu Z, editors. Washington (DC): U.S. Global Change Research Program. 878 p. *https://doi.org/10.7930/SOCCR2.2018*

Ustin SL, Khanna S, Lay M. 2021. Remote sensing of the Sacramento–San Joaquin Delta to enhance mapping for invasive and native aquatic plant species. [accessed 2023 Jan 25]. Davis (CA): Dept. of Land, Air, and Water Resources, University of California, Davis. 44 p. Available from: *https://knb.ecoinformatics.org/knb/d1/mn/v2/object/urn:uuid:c14116d9-8e11-42e0-b9ed-449fe2538944*

Valach AC, Kasak K, Hemes KS, Anthony TL, Dronova I, Taddeo S, Silver WL, Szutu D, Verfaillie J, Baldocchi DD. 2021. Productive wetlands restored for carbon sequestration quickly become net CO2 sinks with site-level factors driving uptake variability. PLoS ONE. [accessed 2022 Oct 07];16(3):p.e0248398. *https://doi.org/10.1371/journal.pone.0248398*

Wang H, River M, Richardson CJ. 2019. Does an 'iron gate' carbon preservation mechanism exist in organic–rich wetlands? Soil Biol Biochem. [accessed 2022 Oct 07];135:48–50. *https://doi.org/10.1016/j.soilbio.2019.04.011*

Ward ND, Megonigal JP, Bond–Lamberty B, Bailey VL, Butman D, Canuel EA, Diefenderfer H, Ganju NK, Goñi MA, Graham EB, et al. 2020. Representing the function and sensitivity of coastal interfaces in Earth system models. Nature Comms. [accessed 2022 Oct 07];11(1):1–14. *https://doi.org/10.1038/s41467-020-16236-2*

Whipple AA, Grossinger RM, Rankin D, Stanford B, Askevold R. 2012. Sacramento–San Joaquin Delta historical ecology investigation: exploring pattern and process. Richmond (CA): San Francisco Estuary Institute–Aquatic Science Center.

Williams PB, Orr MK. 2002. Physical evolution of restored breached levee salt marshes in the San Francisco Bay estuary. Restor Ecol. [accessed 2022 Oct 07];10(3):527–542. *https://doi.org/10.1046/j.1526-100X.2002.02031.x*

Windham–Myers L, Cai W-J, Alin SR, Andersson A, Crosswell J, Dunton KH, Hernandez–Ayon JM, Herrmann M, Hinson AL, Hopkinson CS, and 11 others. 2018a. Tidal wetlands and estuaries. In: Cavallaro N, Shrestha G, Birdsey R, Mayes AM, Najjar RG, Reed SC, Romero–Lankao P, Zhu Z, editors. Second state of the carbon cycle report (SOCCR2): a sustained assessment report. Washington (DC): US Global Change Research Program. p 507–567. Available from: *https://carbon2018.globalchange.gov/chapter/15/*

Windham–Myers L, Bergamaschi BA, Anderson FE, Knox SH, Miller RL, Fujii R. 2018b. Potential for negative emissions of greenhouse gases (CO_2, CH_4 and N_2O) through coastal peatland re-establishment: novel insights from high frequency flux data at meter and kilometer scales. Environ Res Lett. [accessed 2022 Oct 07];13(4):045005. Available from: *https://iopscience.iop.org/article/10.1088/1748-9326/aaae74/meta*

Ye R, Horwath WR. 2016. Nitrous oxide uptake in rewetted wetlands with contrasting soil organic carbon contents. Soil Biol Biochem. [accessed 2022 Oct 07];100:110–117. *https://doi.org/10.1016/j.soilbio.2016.06.009*

ADDITIONAL REFERENCES

California 2030 Natural and Working Lands Climate Change Implementation Plan. [accessed 2022 Oct 07]. Available from: *https://ww2.arb.ca.gov/sites/default/files/2020-10/draft-nwl-ip-040419.pdf*

Enhancement of Delta Smelt (*Hypomesus transpacificus*) habitat through adaptive management of invasive aquatic weeds in the Sacramento–San Joaquin Delta & Suisun Marsh. [accessed 2022 Oct 07]. Available from: *https://drive.google.com/file/d/1xBUdOFJuYt8wZpCEbKP2_ZyZHailhO71/view?usp=sharing*

Suisun Marsh Habitat Management, Preservation, & Restoration Plan. [accessed 2022 Oct 07]. Available from: *https://suisunrcd.org/resources/links/*

NOTES

Siegel S. 2022. Personal communication with Lisamarie Windham–Myers on upland ecosystems in the Delta.

https://doi.org/10.15447/sfews.2023v20iss4art7