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

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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.

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 (CO₂), 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 CO₂, methane (CH₄), and nitrous oxide (N₂O)—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

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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 CO₂ fluxes into soils are the primary route to net negative emissions in the Delta and Suisun Bay, with CH₄ 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 (CO₂) 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 CO₂, as is soil C accumulation. Positive emissions of CO₂, 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 CO₂ stocks, globally, and

is distinctly related to land-management decisions (Canadell et al. 2007).

Aquatic ecosystems are capable of negative CO₂ 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 (CH₄) 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., CH₄ emission, soil oxidation and CO₂ emission) or sink (e.g. belowground productivity, soil C storage). Compared with CO₂, the metabolic products CH₄ and nitrous oxide (N₂O) are both more powerful GHGs (gram for gram) than CO₂ but also are shorter-lived in the atmosphere. As such, over 100-year time-frames, CH₄ and N₂O are, respectively, 21 and 310 times more powerful GHGs than CO₂ (IPCC 2014), and even more powerful over a 20-year time-frame (56 and 298 times, respectively; 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 CH₄ (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 CO₂ (Deegan et al. 2012) and N₂O (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 CH₄ 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 = 10¹² 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 (Bridgman 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 = 10⁹ 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 (CO₂) or the creation of other GHG such as the secondary metabolic products CH₄ and N₂O. 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

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

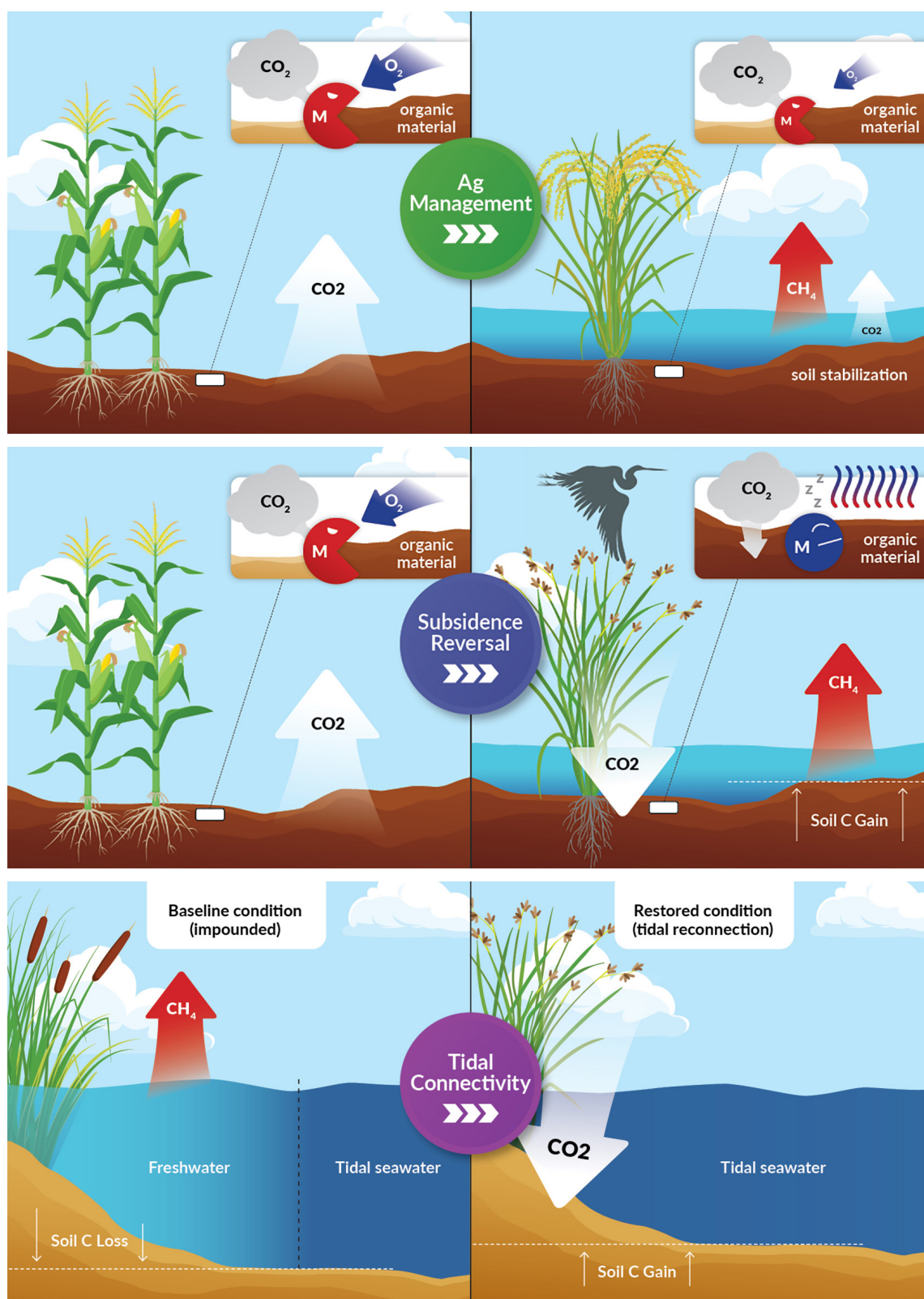


Figure 1 Three interventions, including (A) agricultural hydrologic management via flooding, such as in rice agriculture, (B) impounded wetland construction to reverse subsidence, and (C) tidal connectivity restored or maintained. M = microbial activity. *Source and credit: Figures adapted from Stern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

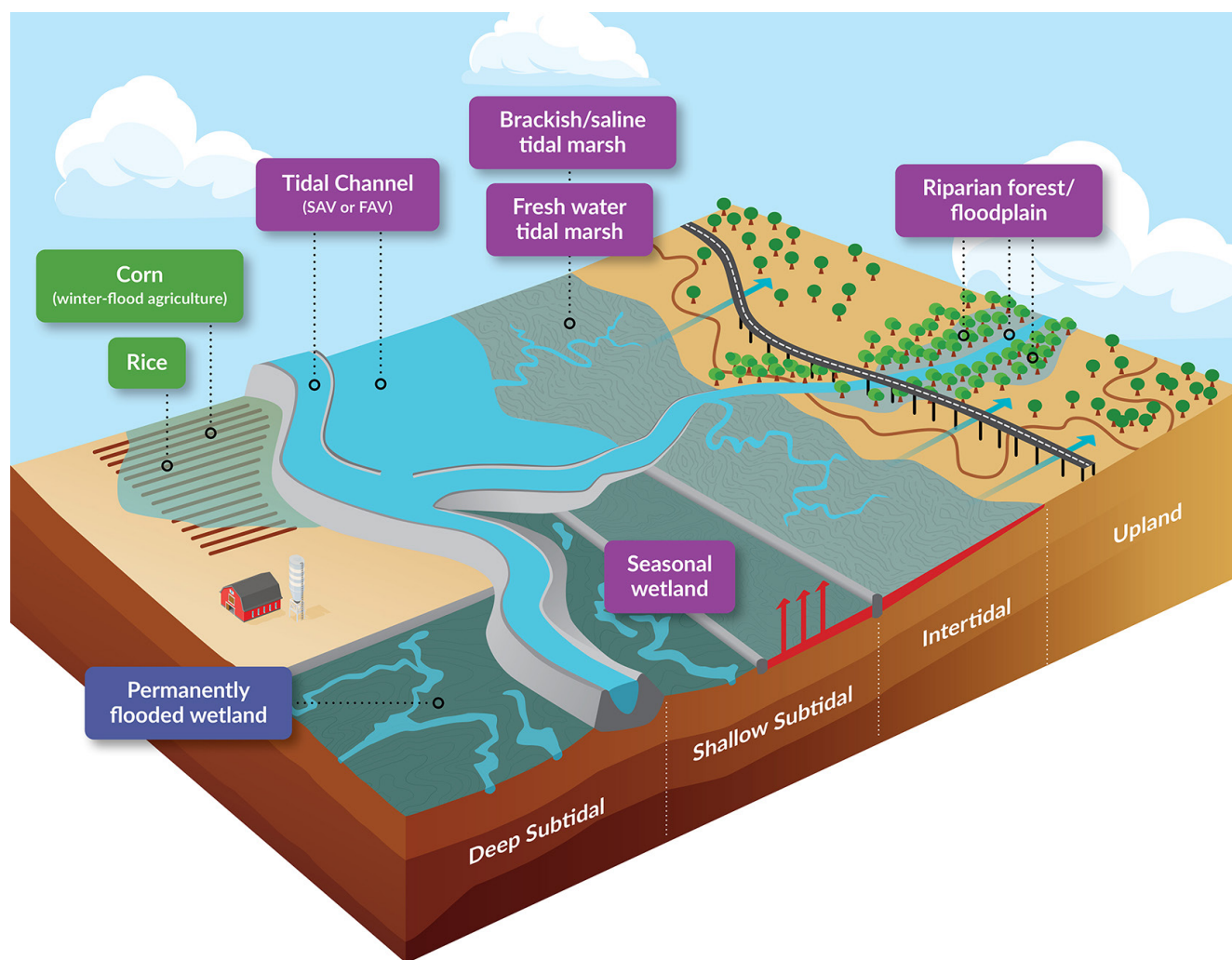


Figure 2 Land-use types of interest to carbon sequestration and/or GHG mitigation across the relative tidal elevation range in Suisun Bay and Delta lands. Corn indicates conventional row crops. Tidal channel refers to open-water aquatic habitats, whether deep or shallow (such as flooded islands) and 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 CO₂ and Reduce CH₄ 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 CO₂ 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 CO₂ Uptake and to Reduce CH₄ 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 ($\sim 0.04 + -0.01 \text{ g C cm}^{-3}$ (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

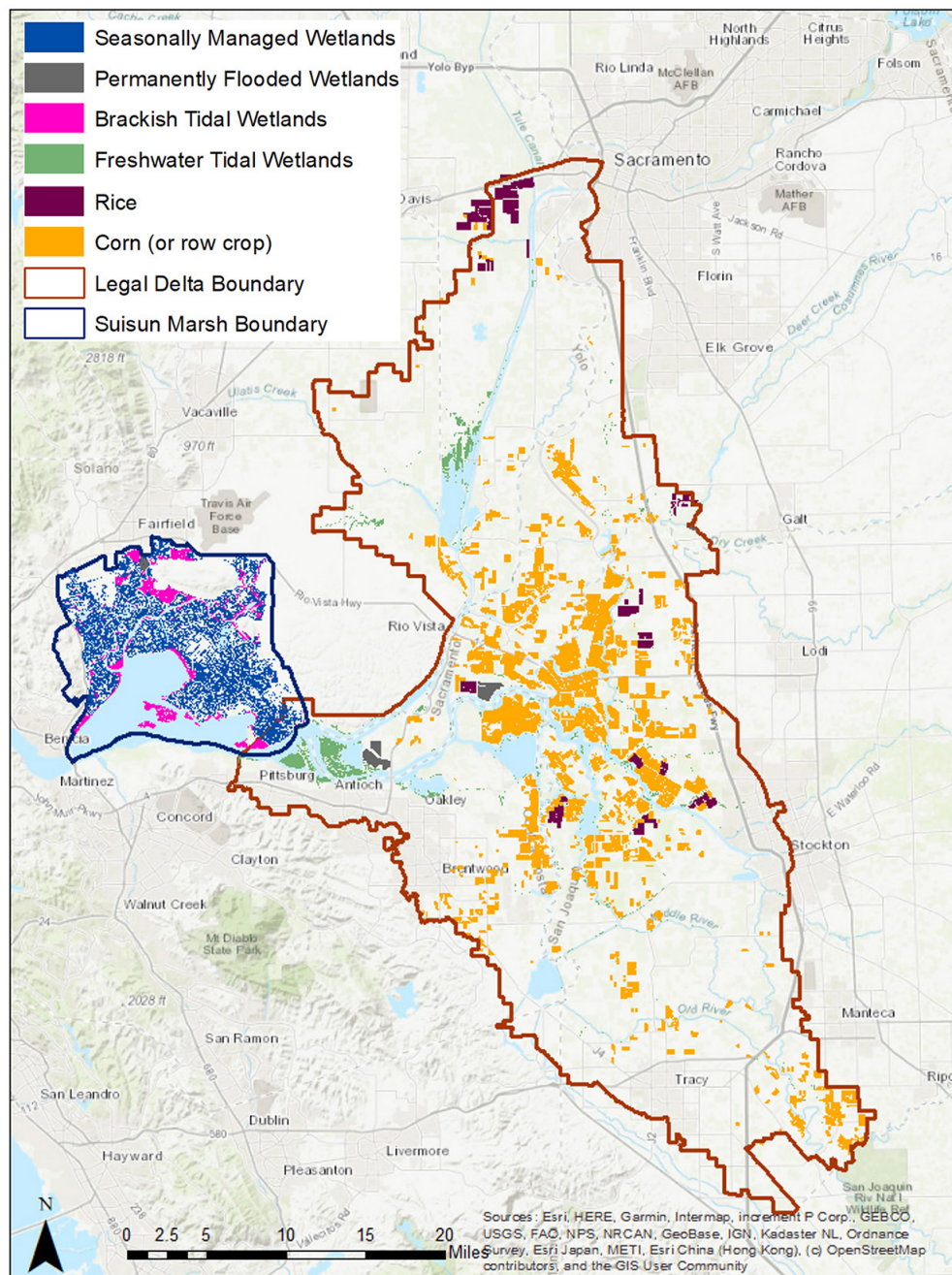


Figure 3 Natural ecosystems and managed lands in the Delta and Suisun Bay considered in this study of GHG-mitigation potential. Categories = (1) row crop agriculture (such as, corn), (2) rice agriculture, (3) permanently flooded wetlands (managed), (4) seasonally managed wetlands, (5) freshwater tidal 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)

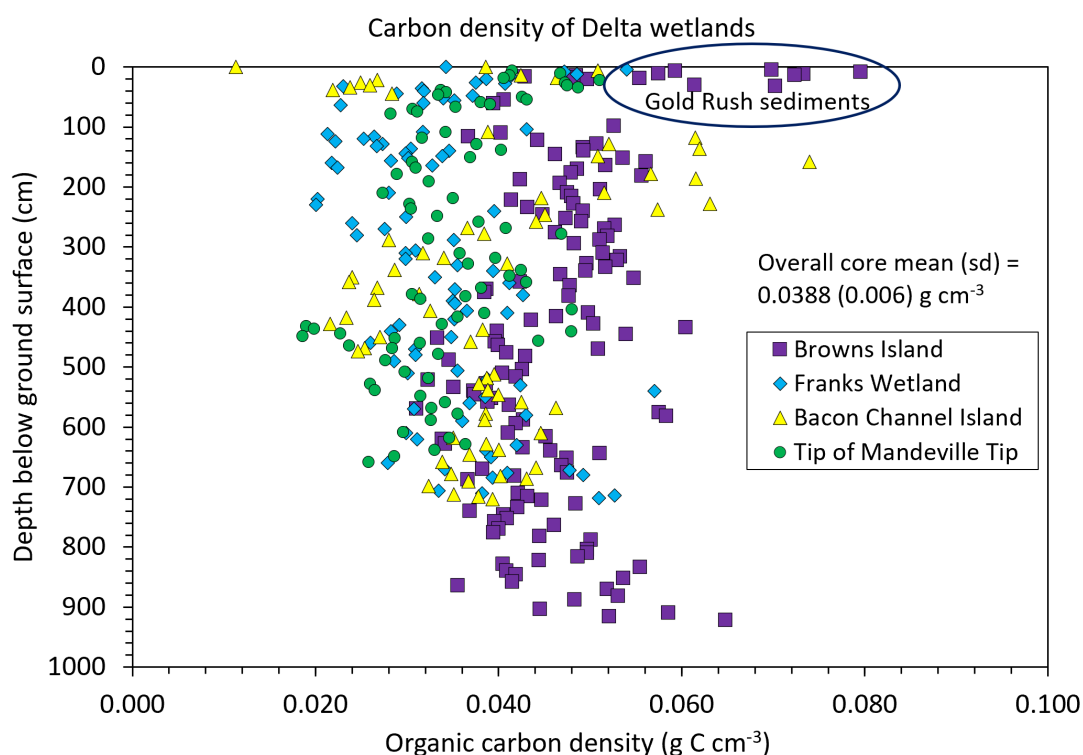


Figure 4 Carbon densities (calculated as organic carbon by weight x dry bulk density, in 2-cm increments) along soil profiles from four deep-soil cores collected in Delta wetlands. Sources: Data from Drexler et al. 2009a, 2016.

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 CO₂ off-gassing from wetland soils is akin to putting out “millions of small fires” (sensu NASEM 2019). Rates of CO₂ 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 CO₂ 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

(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 (Bridgman et al. 2008). Because GHG can also be mitigated by reducing microbially-produced CH₄ emissions or N₂O 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; Bridgman 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 CH₄ 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 CH₄ 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 CO₂ emissions (Miller et al. 2011; Anderson et al. 2016; Hemes et al. 2018), impoundment also generates some of the highest CH₄ emissions ever measured among natural land-covers (Knox et al. 2021). In contrast, alternating wetting and drying (e.g., seasonally or tidally) can reduce CH₄ 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 CO₂ 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 CH₄-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).

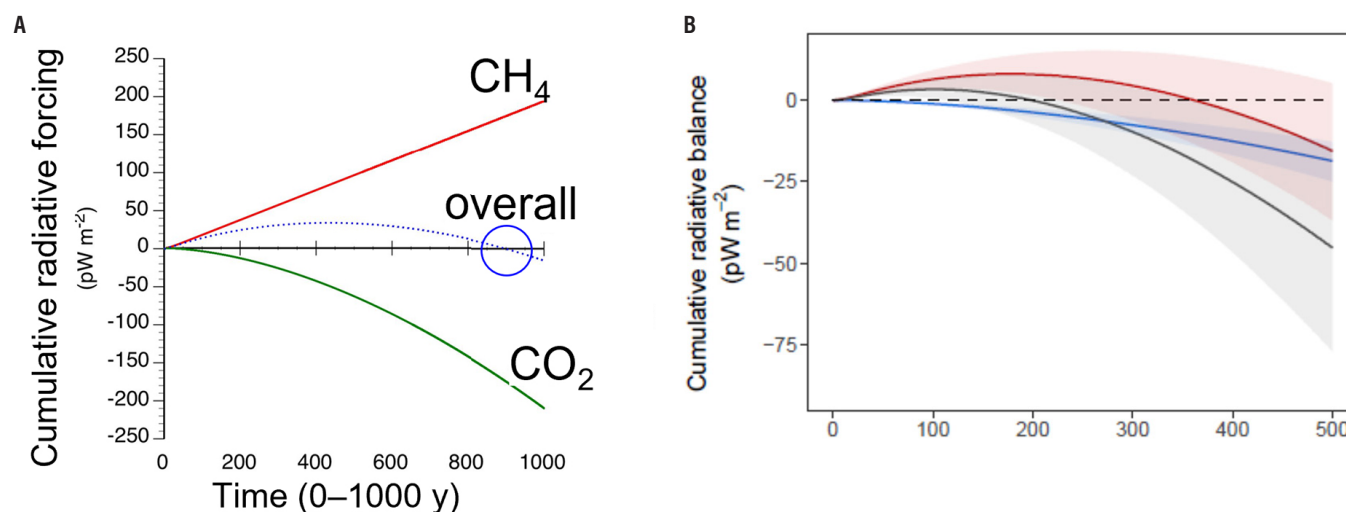


Figure 5 Cumulative radiative balance and cross-over times from net warming to net cooling effects. **(A)** Annual radiative balance for a freshwater tidal marsh in Virginia, reprinted from Neubauer 2021. The *blue circle* represents the crossover time for a freshwater marsh in Virginia, where emission 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.

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 2×10^6 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 $10 \text{ mg } \text{N}_2\text{O m}^{-2} \text{ d}^{-1}$), 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.

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 CO₂, CH₄ and N₂O. 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 CO₂, CH₄ and N₂O, respectively.

We note here that while decades (collectively) of eddy covariance data within the Suisun–Delta complex are available to parameterize CO₂ fluxes in intertidal and permanently flooded managed wetlands, and protocols have been developed to model these rates (e.g., Oikawa et al. 2017), CH₄ and N₂O 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 CH₄ and N₂O 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 CH₄ emissions at levels that exceed tidal lands (13 g CH₄ 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 MTCO₂ 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 MTCO₂ 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 MTCO₂ eq. (> USD 15), and prices are projected to rise to over USD 30 per MTCO₂ 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 km² landscape has shifted to two dominant land-cover types: agricultural land (~1,750 km²) and open water (~250 km²). Very few parcels of agricultural land are poised for tidal reconnectedness because of historical elevation loss and operational constraints (Deverel et al. 2020). Thus, reconnectedness 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

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 CO₂. 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 CH₄ 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 CO₂ uptake, maintained by tidal refreshment.

Third, the benefit of tidal reintroduction is the microbial inhibition of CH₄ 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 CO₂ and marginal emissions of CH₄. 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⁻²y⁻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 $200 \text{ g C m}^{-2} \text{ y}^{-1}$; 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 reconnectedness) 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 $3 \text{ MT CO}_2 \text{ eq y}^{-1}$). 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 $2,050 \text{ CO}_2 \text{ eq m}^{-2} \text{ y}^{-1}$). 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 ($-1,011 \pm 10^3 \text{ g CO}_2 \text{ eq m}^{-2} \text{ y}^{-1}$). 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 $0.2 \text{ MT CO}_2 \text{ eq y}^{-1}$ from these nine sub-habitats, under current extents and management strategies that contribute to the GHG footprint of Delta lands (2 to $3 \text{ MT CO}_2 \text{ eq y}^{-1}$).

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

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 ₂ O (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 fresh-water (this # includes some of the subsidence reversal projects): 5,931. CO₂eq conversions at 45x CH₄ (SGWP) and 298x N₂O. Limited data for N₂O. Wide Range (highly negative to highly positive) = WR. All intertidal and sub-tidal lands assume N₂O 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 CO₂ emissions through raising the water table on agricultural soils in the central Delta (e.g., growing rice with AWD), and (2) halting CH₄ 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 CO₂-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 CO₂ eq y⁻¹). Because of the extent and CO₂ 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 CO₂ eq m⁻²y⁻¹ to 1860 CO₂ eq m⁻²y⁻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 CH₄ 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

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 CO ₂ 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: CO ₂ 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 reconnectedness—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 CO₂ 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 CH₄ 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 CO₂ fluxes can be modeled to some degree across Delta habitats (Oikawa et al. 2017), large uncertainties remain in current CH₄ and N₂O 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 CH₄ 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.

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