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Science to Inform Management of Subsided Lands in the Sacramento-San Joaquin Delta

Delta Independent Science Board

Draft Review (08/14/2026)

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All links in this document have been created with meaningful text. If you have a printed copy of this review, you can find the electronic version of this report on the Delta ISB's meetings webpage for the August 2026 meeting: https://deltacouncil.ca.gov/delta-isb/meetings.

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Executive Summary

Across the Sacramento-San Joaquin Delta, draining of historic freshwater tidal wetlands for agriculture has resulted in oxidative degradation of carbon-rich peat soils and associated loss of land surface elevation – a phenomenon known as subsidence. Consequently, subsidence in the Delta contributes to greenhouse gas (GHG) emissions and increases hydrologic pressure on more than 1,100 miles of levees, which increases flood risk and requires costly management action to maintain the viability of agricultural lands. Currently, there are approximately 150,000 acres of deeply subsided lands in the Delta. A key tool for mitigating subsidence involves re-inundation, such as wetland restoration, rice cultivation, floating tule wetlands, and wetland-crop mosaics.

To evaluate the state of science related to managing subsided lands, the Delta Independent Science Board (Delta ISB) conducted a review to understand science advancements and opportunities related to efforts to a) slow or reverse subsidence and b) reduce or reverse GHG emissions from the Delta. This review was based on the Delta ISB's reflections from a workshop in 2023, discussions with subject matter experts, a literature review, and public comments. The findings and recommendations, largely based upon the workshop in 2023, are found in the table below.

Findings	**Challenges**	**Recommendations**
Subsided Land Management and Research		
Inundating peat soils through managed wetlands, rice cultivation, floating tule wetlands, and land-use mosaics have already halted or reversed subsidence on multiple islands with more than 20 years of field research.	Research and coordination is fragmented; although collaboration happens informally.	The Delta ISB sees an opportunity for a strategic long-term program to align priorities, share lessons, or standardize data collection across all subsidence-reversal efforts. This will help accelerate progress through coordinated science and management.
Biogeochemistry of Greenhouse Gas Emissions and Carbon Sequestration		
Efforts to inundate peat soils in the Delta can reduce carbon dioxide emissions and enhance long-term carbon sequestration. About 1.2 million metric tons of carbon dioxide are emitted each year from	While the science of the biogeochemistry to inform peat soil inundation is strong, strategies such as rice cultivation and wetland restoration involve tradeoffs. For instance, flooded	The Delta ISB highlights an opportunity to advance scientific knowledge in ways that can improve subsidence-management performance. Additional research on methane and nitrous oxide

Findings	Challenges	Recommendations
oxidizing peat soils, while wetland and rice restoration can lower emissions by 1 to 5 metric tons carbon dioxide equivalent per acre per year. Sequestration can provide an economic benefit when certified by entities such as the American Carbon Registry.	conditions reduce carbon dioxide but can increase methane and nitrous oxide production.	dynamics, soil and hydrologic processes, and model development will help optimize the effectiveness of strategies.
Agricultural Practices in the Delta		
Paludiculture, especially rice, is one of most practical agricultural solutions. Rice production is familiar to growers, economically viable, and keeps soils saturated, directly addressing peat oxidation.	High up-front conversion costs remain a barrier. Farmers perceive substantial financial risk in switching from conventional crops to rice.	The Delta ISB recommends more detailed cost-benefit data analysis and modeling to strengthen the design of incentive programs for landowners. Leveraging social science to improve knowledge transfer among farmers, assessing the viability of alternative paludiculture crops, and evaluating incentive structures for wetland conversion were also recommended.
Delta Landscape Challenges		
The Delta's diverse physical, social, and agricultural landscapes create broad opportunities for reversing subsidence and offering co-benefits like carbon sequestration.	These different landscapes also make subsidence management complex; key co-benefits and tradeoffs (including water quality impacts of expanded rice farming) remain insufficiently quantified or modeled across the region.	The Delta ISB emphasizes the importance of quantifying and refining the effects and tradeoffs of different public and private incentives for inundating Delta lands.

Implementation of the recommendations from the Delta community is already underway, as this report was being finalized. For example, The Sacramento-San Joaquin Delta Conservancy and The Nature Conservancy formed the Delta Carbon Team in March 2025, a collaborative group working to advance and coordinate the implementation of subsidence and emission reducing projects in the Delta, while addressing the Delta ISB recommendations. Thus, the Delta community is committed to addressing subsidence now, while continuing to improve the science that supports long-term management.

This review shows that subsidence-reversal projects are already underway and much has been learned from these projects. Continued scientific work will help refine and optimize these efforts in the years ahead, and the Delta ISB's recommendations provide guidance for doing so. Building upon this review, the Delta ISB also plans to embark on a broader review on nature-based solutions, which can further explore some of the challenges such as quantifying co-benefits, highlighted in this review.

Problem Statement

Peat soils in the Sacramento-San Joaquin Delta (Delta) have unique properties and behavior, requiring different management than other agricultural soils in California and other parts of the world. Since the late 19th century, draining historic freshwater tidal wetlands for agricultural cultivation has caused the land surface to steadily lose elevation, a phenomenon known as subsidence. Subsidence in the Delta is caused primarily by the decomposition (microbial oxidation) of organic matter in the root zone when it is dewatered. Although peat soils experience some initial compaction when they are first drained, studies show that long-term subsidence in the Delta is driven primarily by microbial oxidation of organic matter, not physical compaction, a key difference from other peatland regions (Deverel et al., 2016b). Portions of the central and western Delta have subsided as much as 30 feet (9 meters) below sea level (Figure 1). The Delta is over 738,000 acres (298,658 hectares) and spans six counties. Approximately 150,000 acres (~60,703 hectares) of land in the Delta are deeply subsided (i.e., below -16 feet or -5 meters; see Figure 2).

Today, more than 1,100 miles of levees – initially built to facilitate the drainage of freshwater wetlands – are required to protect farmland, housing, and critical infrastructure from flooding. Rates of sea level rise during the last two millennia have been so slow (0 to 0.2 millimeters/year) that sea level has been essentially unchanging, i.e., stationary. Now sea level rise is accelerating, i.e. non-stationary, caused by global warming associated with climate change. According to the State of California Sea Level Rise Guidance (OPC 2024), sea levels are likely to rise between 1.6 to 3.1 feet (0.48 meters to 0.94 meters), with an upper range projection of 6.6 feet (2.01 meters) by 2100.

While sea level rise alone is important, what ultimately matters for levees, agriculture, and infrastructure is relative sea-level rise (RSLR), which is the change in sea level relative to the land surface. RSLR reflects how rapidly sea level is rising relative to the sinking Delta islands. Recent analysis of 50 Delta tidal gauge records shows that RSLR varies widely across the region, ranging from -2.8 to +12.9 millimeters/year, with most stations experiencing RSLR above the coastal rate of 3.3 millimeters/year (Baranes et al., 2023).

Without significant human intervention to reduce global warming, sea levels will continue to rise in the coming centuries. It is anticipated that ongoing sea level rise and increased riverine flooding from climate change will increase stress on Delta levees, requiring more active intervention to prevent floods. In addition, seismic activity within the Delta or its surroundings also threatens levee stability, both directly from local surface ruptures and indirectly from shaking-induced soil liquefaction. A major levee breach could disrupt water deliveries to the two-thirds of Californians in southern California who rely on Delta water (Mount & Twiss, 2005).

Ongoing subsidence within 500 feet of the levee crown (known as Zone of Influence in the CALFED Record of Decision), combined with increasing hydrologic pressure driven by climate change (which threatens levee stability), has prompted governmental agencies and other institutions to implement 'nature-based' approaches to manage subsided lands. One promising nature-based approach being instituted in the Delta under the leadership of the Sacramento-San Joaquin Delta Conservancy and the California Department of Water Resources (with the support of other institutions) is managed re-inundation of the landscape via freshwater wetland creation or rice cultivation. Mesocosm-and pilot-scale projects initiated in 1993 on Twitchell Island demonstrate that intentionally inundating land to establish managed freshwater wetlands can reverse subsidence (Deverel et al., 1998; Miller et al., 1998). More recent research indicates that rice cultivation can slow or arrest subsidence (Deverel et al. 2016b).

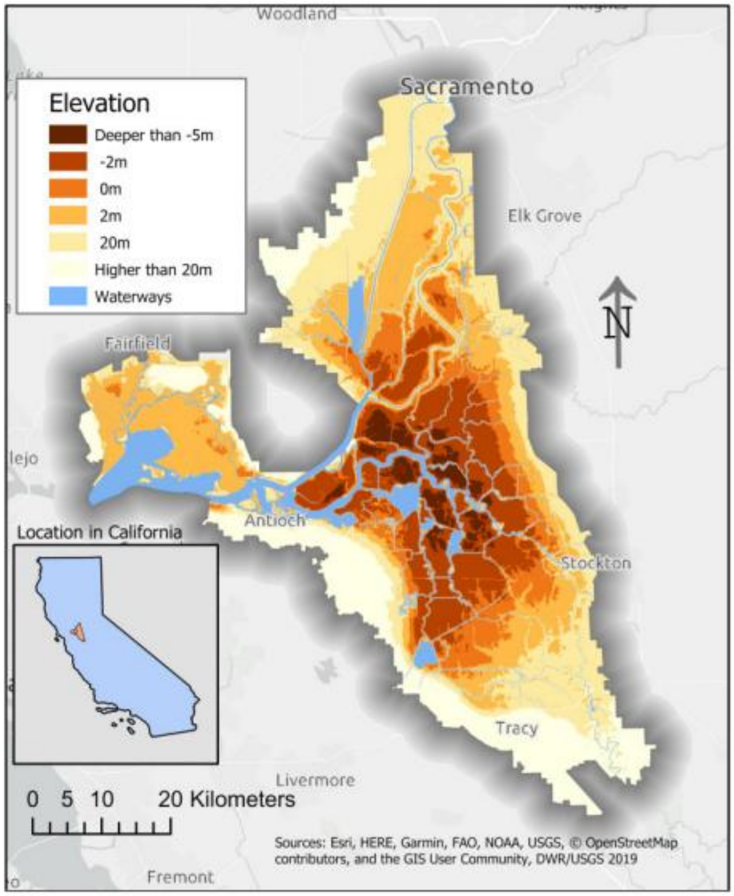


Figure 1. Map of elevations in the Sacramento-San Joaquin Delta where subsidence has occurred. An elevation of 0 m indicates sea level, while negative elevations are below sea level. Elevation deeper than -5 m are areas that are deeply subsided. Map used with permission from Stern et al., 2022.

Although deeply subsided areas represent less than 2% of California's croplands, they produce approximately 13% of statewide cropland greenhouse gas emissions. The Delta is currently estimated to emit ~1.2 million metric tons of carbon dioxide (CO_2) per year due to ongoing oxidation of peat soils (Vaughn et al., 2024). These emissions are disproportionately large because peat soils, though covering only ~3% of global land area, store roughly 20% of all terrestrial carbon (Limpens et al., 2008). Therefore, continued oxidation of Delta peat represents both a regional management challenge and a globally relevant climate concern.

A collateral benefit of inundation is that this intervention avoids carbon dioxide emissions released by the microbial oxidation of peats and, in the case of managed wetlands, promotes sequestering of carbon by biomass accumulation. Over time, if implemented at a large scale, these practices could convert the Delta from a significant **source** of carbon dioxide emissions, an important greenhouse gas (GHG), to a major **sink.** Methane is another potent GHG that is produced by subsidence management strategies and the production of methane, which contributes to the net GHG balance, will be discussed in depth later.

Purpose of Review

Given the risks subsidence poses to levee stability, water supply, climate emissions, and Delta agriculture, the Delta Independent Science Board (Delta ISB) under its legislative mandate, has synthesized and evaluated the state of science related to managing subsided lands. This review is intended to inform ongoing and future management of subsided lands by describing what is understood about subsidence, determining where science can improve current efforts, identifying knowledge gaps, and summarizing the current and potential incentives for different management actions on subsided lands, such as wetland restoration and agricultural land management. The broad nature of the review is intended to serve a diverse audience that includes Delta managers, researchers, legislators, and decision-makers from local, state, and federal agencies, and other interested parties.

This report is divided into two main sections. The first part contains the key findings and recommendations by the Delta ISB, along with current momentum towards implementing the recommendations. These are addressed to governmental agencies and landowners who directly manage or support management of subsided land in the Delta, and those agencies that conduct or fund science related to managing subsidence in the Delta, such as the Delta Science Program through its science prioritization via the Science Action Agenda (DSC 2022) and funding processes.

The second section provides both a contextual background on Delta subsidence issues, and summaries of the workshop panel presentations and discussions that the Delta ISB hosted in October 2023, which was a key resource for informing the findings and recommendations. The report is structured to present the Delta ISB’s findings and recommendations up front, ensuring that readers can quickly understand the Delta ISB’s conclusions. The contextual material is provided in a separate section so that the workshop insights and the scientific reasoning that support those conclusions are transparent without obscuring the main messages. Links to online recordings of panelist presentations and discussions are also provided.

Part 1: Findings, Recommendations, and Current Momentum

Summarized here are the key findings and recommendations developed by the Delta ISB, following a public workshop held in Sacramento on October 19 to 20, 2023, which focused on basic and applied science needed for improving management of subsided lands in the Delta (Figure 1). The workshop primarily addressed the science behind two active and major ongoing management efforts: (1) to slow or reverse subsidence and (2) to reduce or reverse GHG emissions from the Delta. “Science” here includes social, biophysical and biogeochemical sciences.

The findings and recommendations are mainly based on the Delta ISB’s synthesis of the presentations and discussions at the workshop. Findings and recommendations are organized around the following topics, which correspond to the main sessions at the workshop”

1) Subsided land management and research,
2) Biogeochemistry of greenhouse gas emissions and carbon sequestration,
3) Agricultural practices in the Delta, and
4) Delta landscape challenges.

The findings and recommendations are also informed by the Delta ISB’s expertise on scientific approaches and tools that can address identified gaps in current subsidence-related science, and a limited review of literature on Delta subsidence. Lastly, the Delta ISB drew upon interviews with experts on both subsidence and subsidence-related issues in the Delta and considered public comments throughout the process.

The first public draft of this report was released in July 2024 with the Delta ISB’s draft findings and recommendations. As the Board worked to finalize this report, new scientific advancements continued to be made, and some of the Delta ISB’s recommendations were implemented. This ongoing progress underscores both the dynamic nature of subsidence-related science and the strong interest among partners in moving subsidence-reversal strategies forward. Current progress to address the Delta ISB's recommendations are summarized in the "Next Steps: Building off Current Momentum" section.

Subsided Land Management and Research

Findings

Active and Emerging Subsidence-Mitigation Strategies in the Delta

Types of active and planned projects in the Delta to mitigate land subsidence include:

1) reversing subsidence by managed wetland restoration,
2) slowing or arresting subsidence by cultivating rice,
3) developing floating tule wetlands in deeply subsided islands (e.g., Deverel et al., 2024),
4) construction of toe berms along levees that can reduce risk and consequences of subsidence, and
5) designing a landscape, i.e., crop and wetland mosaics, that locates managed wetlands, rice, and other crops based on site-specific soil and hydrologic characteristics such as elevation and drainage (Deverel et al., 2017).

Benefits of these projects include arresting and reversing subsidence, protecting levee stability, avoiding carbon emissions, carbon sequestration, and habitat restoration. As an example, based on multiyear ecosystem flux measurements summarized in Hemes et al. (2019), land use conversions from drained agricultural peat soils to restored wetlands on Twitchell Island and Sherman Island consistently reduce net greenhouse gas emissions. Depending on the preceding agricultural land use and the successional stage of the restored wetland, annual greenhouse gas emission reductions generally range from approximately **1 to over 5 metric tons of carbon dioxide (CO_2) equivalent per acre per year,** with the largest reductions occurring when converting high emission crops such as corn to fully vegetated restored wetlands (Hemes et al., 2019).

Current and Planned Efforts

Current and planned efforts to manage subsided land in the Delta include managed wetlands and wetland-rice mosaics on Sherman, Twitchell, Webb, Bethel, and Staten Islands, along with a pilot project for floating tule wetlands on Bouldin Island (Figure 2). To date, the Department of Water Resources, the Sacramento-San Joaquin Delta Conservancy, and other partners have planned or implemented the conversion of 20,746 acres (8,396 hectares) of non-inundated agricultural land to rice, and 8,363 acres (3,384 hectares) of wetlands (see Figure 2), which avoids more than 291,000 tons of CO_2 emissions annually using the low end estimate from Hemes et al. 2019. Recently released state-wide targets for Natural and Working Lands target an additional 50,000 acres (20,234 hectares) for managed freshwater wetlands and rice cultivation by 2045 (see California Climate Targets Appendix in CNRA 2024). The agencies and organizations supporting these land conversions are primarily the Sacramento-San Joaquin Delta Conservancy, California Department of Water Resources, Metropolitan Water District of Southern California, and The Nature Conservancy.

Collaboration in these projects is diverse, including farmers, consultants, agencies, and institutions, and has provided insights for future planned efforts. Much has been accomplished and learned about slowing and reversing subsidence and factors that control GHG emissions from the last 20+ years of research on pilot and full-scale implementation projects in the Delta.

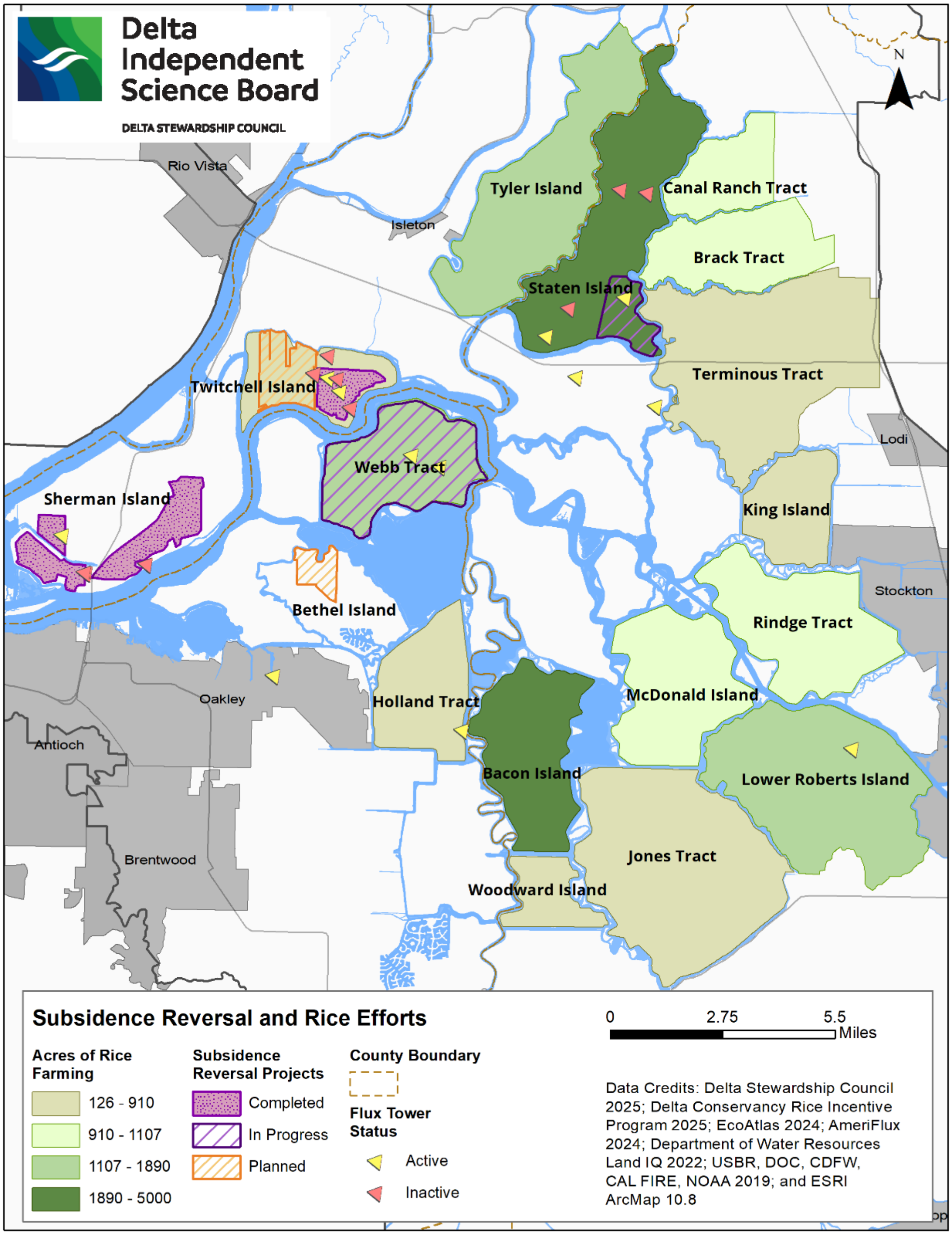


Figure 2. Subsidence reversal efforts in the deeply subsided areas of Delta along with flux towers and current rice cultivation that are completed, in progress or planned. Total acreage of all the rice projects is ~20,746 acres (8,396 hectares). Total acreage wetlands from subsidence reversal projects is ~ 8,363 acres (3,384 hectares). Active flux towers are those with an end date of 2023 in AmeriFlux or confirmed to be active through personal communications. Inactive flux towers are those that have not been updated in AmeriFlux since 2023.

Recommendations

Substantial progress has been made, and existing projects have generated valuable new insights into subsidence-reversal processes. Building on this momentum, there is an opportunity to deepen scientific understanding, as highlighted in the sub-sections below. To support continued learning through adaptive management and address current science needs, **the Delta ISB recommends establishment of a strategic long-term program to monitor, document, and further understand the geotechnology and biogeochemistry of all subsidence reversal projects occurring in the region**. Establishing a long-term program would accelerate progress through coordinated science and management and directly support the needs outlined below. For example, this review required creating an inventory and map of existing subsidence-reversal projects and eddy covariance flux towers (Figure 2), illustrating the value of a sustained, coordinated approach to tracking and sharing information.

Knowledge Gaps in Decadal-Scale Subsidence Processes

Subsidence and the underlying soil consolidation caused by drainage of peat soils are broadly understood at the millennial time scale at which the Delta peats were created. However, the understanding of the factors that control and affect subsidence processes and subsidence reversal rates in organic soils at decadal time scales are less well documented, which includes primary and secondary consolidation, organic soil density, temperature, depth to groundwater table, and biomass accumulation and degradation. There is an opportunity to learn from past, current, and future projects.

Improved understanding of these factors is important given interest in whether subsidence-reversal practices might eventually contribute to levee stabilization. Consolidation behavior and soil density determine how quickly new organic material can accumulate enough mass and strength to offer structural support. In contrast, public comments highlighted how engineered approaches such as toe berms rely on mineral soils with unit weights around 110 pounds per cubic foot (pcf), compared with roughly 8 pcf for dry peat and about 70 pcf when saturated. Replicating the stabilizing mass of a toe berm through peat accretion alone would require a very thick organic layer and would take many years to develop.

Research has also begun to clarify these dynamics. Deverel et al. (2014) simulated decadal-scale accretion on Twitchell Island, providing insight into both consolidation and biomass accumulation processes, and Deverel et al. (2020) documented 20 years of measured accretion at comparable rates. In terms of groundwater depth, accretion occurs only where soils remain inundated, meaning that lowering the groundwater table, or failing to maintain surface saturation, would inhibit organic-matter accumulation and limit or halt accretion. Collectively, there is an opportunity for continued long-term research, as projects are underway, to better understand the feasibility, rates, and limits of subsidence reversal under different management and hydrologic conditions.

Importance of Long-term Monitoring and Adaptive Management

Institutional focus and commitment to long-term monitoring in areas where subsidence reversal projects are underway will greatly enhance understanding necessary to improve management and restoration since these efforts are attempting to duplicate in decades what nature required millennia to accomplish. Monitoring results and special studies in projects across Delta regions will provide the results needed for future adaptive management.

It is encouraging that instrumentation has already been installed on Twitchell Island and Sherman Island to measure accretion rates, and that land-surface elevation in the rice fields on Staten Island has been monitored since 2021 and will continue to be tracked into the future. Preliminary data from Deverel et al. (in prep) show that land-surface elevations are stable or increasing, with fluctuations linked to changes in groundwater depth. Additional instrumentation is also planned for rice fields on Holland Tract and Roberts Island, further expanding the region's capacity to evaluate subsidence-reversal outcomes. Future projects can learn from the findings from these projects.

Potential for Paludiculture to Reverse Subsidence

There is also a need to further evaluate the potential for rice cultivation and other paludiculture (agriculture on wet or rewetted peatlands) crops to reverse, and not just arrest, subsidence. Research in the Netherlands has demonstrated accretion in experimental paludiculture plots, underscoring the potential for such practices to contribute to subsidence reversal (Temmink et al., 2023).

Water Demand and Resource Management Considerations

Although not extensively discussed at the workshop, projects to manage subsidence (i.e., subsidence reversal wetlands and rice growing) have water demands that can be substantial (Linquist and LaHue, 2020; Baldocchi et al., 2016). However, future research may offer solutions to help address soil and water resource management. Evapotranspiration (ET) measurements on Twitchell Island for rice and managed wetlands, respectively, were about 19 and 21 percent greater than the average ET for the Delta (Eichelmann et al., 2018). It should be noted, however, that Delta water demand may differ from other rice growing regions within California due to differences in soil types, topography, local climatic conditions, or management actions (Linquist and LaHue, 2020).

Sustaining Expertise and Strengthening Partnership

Lastly, maintaining technical and scientific expertise, as well as continuing to engage with interested landowners, tribes, and farmers, will be essential for supporting long-term monitoring. Scientific leadership already involved in these projects includes private consultants, the Sacramento-San Joaquin Delta Conservancy, California Department of Water Resources, Metropolitan Water District of Southern California, and the Delta Science Program/Delta Stewardship Council. The Delta ISB was impressed with the current level of expertise and considers it to be essential that this expertise be maintained. Collaboration with Native American Tribal partners is also important, both to incorporate Tribal Knowledge into project design and management and to help identify and fill knowledge gaps relevant to potential future management of subsided lands.

Biogeochemistry of Greenhouse Gas (GHG) Emissions and Carbon Sequestration

Findings

Carbon Dynamics, Peat Accretion, and Subsidence Risk in Delta Peatlands

Reducing GHG production and enhancing carbon sequestration are potential major co-benefits of arresting and reversing subsidence in the Delta. Wetland vegetation can be an ongoing source of new peat soil as water levels are maintained and raised, and new plant growth produces additional biomass. This peat soil formation is a robust co-benefit of managing land to reduce subsidence because coastal soils, such as those in the Delta, can accrete material and increase their elevation when water level rises and have no limit on storing organic matter. In the 6,700 years that the Delta wetlands have existed, they have been a major sink for carbon and, if left in their natural state, would have continued to sequester carbon (Drexler et al., 2019).

Draining Delta wetlands and practicing dry land farming have promoted the breakdown (via microbial oxidation) of organic matter in the dewatered root zone of the peat soil, releasing CO_2, a GHG. Over the past 150 years, two-thirds of the initial stock of organic carbon in the Delta wetlands has been lost to the atmosphere (Vaughn et al., 2024). The remaining peat in the Delta is thickest in the northern and western Delta (Figure 3). Areas with high potential for future subsidence are regions with deep organic soils that continue to be subjected to oxidation.

The spatial variability of current peat thickness can help predict future subsidence risk and be used to prioritize mitigation efforts. Peat thickness, together with the thickness of underlying tidal mud deposits, controls how vulnerable an area is to under-seepage forces. When these marsh deposits are thin, the risk of under-seepage increases, which in turn raises the likelihood of erosion of levee-foundation materials. This process can compromise levee stability and elevate failure risk (Deverel et al., 2016a). Understanding where peat and underlying sediments are thin therefore helps identify areas with heightened susceptibility to subsidence-related levee hazards and supports more targeted management and restoration planning.

GHG Tradeoffs with Different Subsidence Management Strategies

Whereas the basic GHG chemistry of peat soils is generally understood, there is much to be learned to forecast responses to management actions in the Delta (see Windham-Myers et al., 2023). Different subsidence management strategies, such as paludiculture (including rice farming) and managed freshwater wetlands, have tradeoffs in terms of potential for subsidence reversal, GHG emissions and carbon sequestration (see Figure 4). In addition to CO_2, two other greenhouse gases of concern in wetland management are methane (CH_4) and nitrous oxide (N_2O). While inundating peat soils generally reduces the microbial oxidation of organic matter that produces CO_2, it also creates conditions of low oxygen availability that promote generation ofCH_4 and N_2O, which are potent global warming gases. The available data indicate N_2O emissions for drained organic soils are greater than for rice and wetlands (Anthony and Silver, 2024, Windham-Myers et al., 2018b; Ye and Horwath, 2016).

The biogeochemistry of peat soils depends on specific conditions that can vary spatially and temporally. These conditions include the organic content of the peat soil and the amount of water, oxygen, and reactive solutes, such as sulfate and nitrate, in the porewater of the soil. The preservation of organic matter in peat soils is also influenced by hydrologic conditions and the export of dissolved organic matter to surrounding waterways.

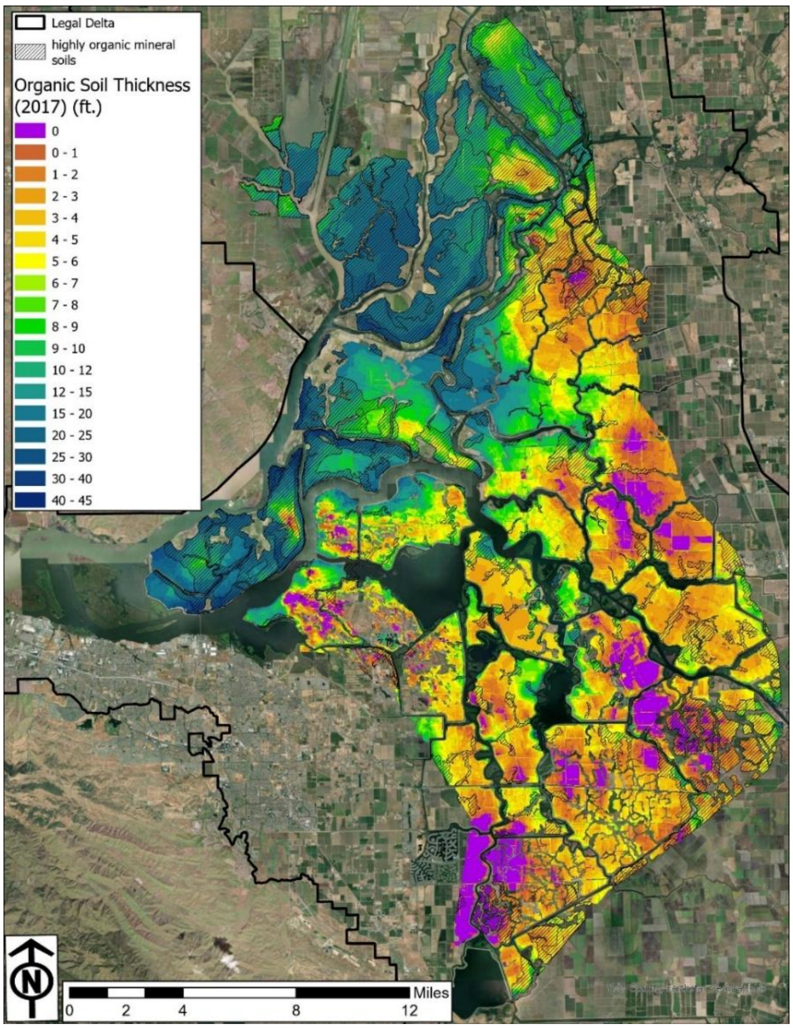


Figure 3. Thickness of highly organic peat soils (solid color) and highly organic mineral soils (hashed markings) (source NRCS SSURGO, used with permission by HydroFocus). Uncolored areas represent mineral soils without peat. Regions with 0 feet organic soil thickness (purple) are regions previously mapped as organic soils or highly organic mineral soils that no longer have remaining peat. Highly organic mineral soils (~7-16% soil organic matter) have lower organic content than highly organic peat soils and thus lower rates of subsidence.

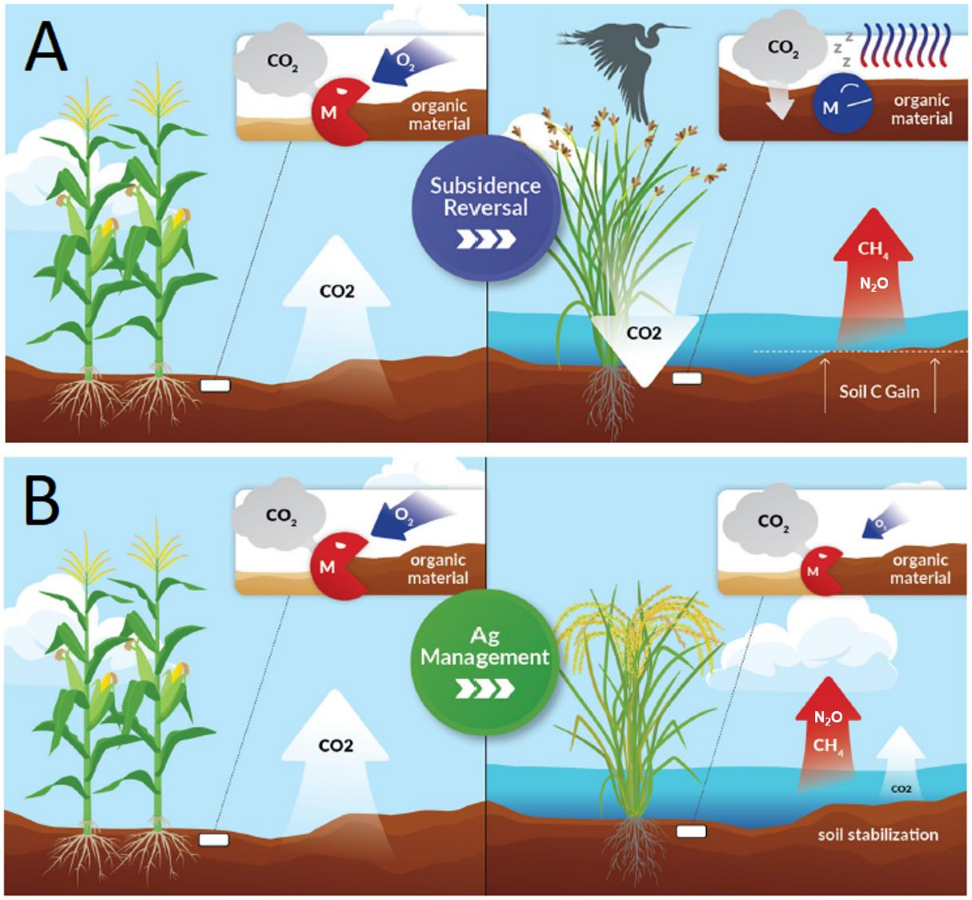


Figure 4. Tradeoff of greenhouse gas (GHG) release and sequestration under two different subsidence management interventions. (A) Shifting from agriculture to managed freshwater wetlands can halt, and reverse, the subsidence process as permanent flooding prevents the oxygen (O_2)-dependent microbial decomposition of organic material and thereby accretes peat from vegetation burial. Managed wetlands can reduce CO_2 emissions from microbial oxidation and sequester atmospheric CO_2 in soils; however, CH_4 and N_2O emissions are increased following conversion compared to drained agricultural land. (B) Agricultural management of shifting to paludiculture (such as rice) can stabilize soils as the introduction of a seasonal surface water layer intermittently halts the oxygen (O_2)-dependent microbial decomposition of peat soils that leads to subsidence, temporarily decreasing, but not eliminating CO_2 emissions. However, CH_4 and N_2O emissions are increased while the land is inundated compared to traditional agriculture. M = microbial activity. Source and credit: Figures adapted from Stern et al., (2022) and taken from Windham-Myers et al., (2023). Illustrated by Vincent Pascual, California Office of State Publishing.

Both CH_4 and N_2O are more potent as GHGs than CO_2 but have half-lives in the atmosphere that are significantly less than the 500+ year half-life for CO_2 (Windham-Myers et al., 2023; Stein and Lidstrom, 2024). CH_4 has about 28 to 30 times the heat trapping ability than CO_2, but with a much shorter persistence in the atmosphere (i.e., a half life of decades rather than centuries). N_2O is an even more potent greenhouse gas (up to 300 times that of CO_2) and persists for longer than CH_4.

One important finding for management of the Delta is that CH_4 and N_2O emissions decrease as the organic carbon content of the soil increases (Ye et al., 2016, Ye and Horwath 2017), and time since inundation (Hemes et al., 2018; Miller, 2011; Windham-Myers et al., 2018a). As CH_4 emissions decrease while wetland soils and plant cover mature, this will shorten the time required for the net cooling effect of carbon dioxide sequestration in the form of peat accumulation to outweigh the net warming effect of CH_4 emissions. This transition point in terms of years since inundation is referred to as the wetland cross-over time. Factors such as salinity can affect the cross-over time for restored wetlands (Figure 5). Freshwater wetlands could take as long as 80 years before reaching the cross-over point.

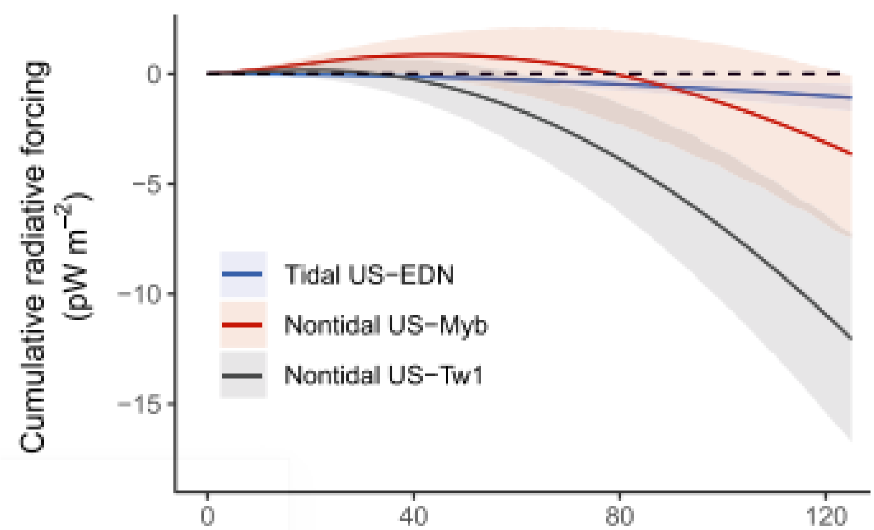


Figure 5. Modeled cross-over times for restored San Francisco Bay and Delta wetlands determined by the change in CH_4 and CO_2 dynamics of wetlands compared to previous land use (cumulative radiative forcing on the y-axis). X-axis represents time since restoration (years). Wetlands achieve a net cooling effect when the cumulative radiative forcing < 0. Factors such as salinity, previous land use, and accretion rates will influence crossover times. EDN = Eden Landing (Bay); Myb = Mayberry (Sherman Island, Delta); Tw1 = West Pond (Twitchell Island, Delta). Figure used with permission from Arias-Ortiz et al. (2021).

For tidal wetlands, methane emissions could potentially be managed by controlling hydrology to obtain favorable water chemistry. For example, sulfate, which is commonly found in seawater, can reduce rates of methane emissions in tidal wetlands (Windham-Myers et al., 2018a). Another notable finding is that negligible methane production occurs in tidal wetlands in which salinity reaches half that of seawater (Poffenbarger et al., 2011; Arias-Ortiz et al., 2024), likely due to marine-based supply of sulfate. Another possible approach that does not increase GHG emissions is to apply metal coagulants, which enhance flocculation and may enhance vertical accretion of peat soils (Hansen et al., 2018; Bachand et al., 2019).

Monitoring Carbon, Methane, and Lateral Fluxes across the Delta

Microbes remain active during the mild winter conditions of the Delta, so CO_2 and CH_4 emissions continue in winter (Bergamaschi et al., 2021). Given the dependence of GHG production on the dynamic conditions in peat soils, year-round monitoring of CO_2 and CH_4 from purposely inundated lands is necessary to provide information for determining net annual GHG emissions. While this is already happening at multiple sites, additional eddy flux towers, which measure how gases like CO_2 and CH_4 move between the land and the air, would improve understanding. A list of the active eddy covariance flux towers located where these measurements have been made in the Delta and Suisun Marsh can be seen in Table 1. It is a challenge to get a handle on N_2O emissions given that many flux towers do not measure this trace gas.

In addition to vertical GHG fluxes, recent research has demonstrated that lateral exports of carbon from drained peat islands represent a substantial and previously under-quantified pathway in the Delta's carbon budget. Richardson et al. (2020) found that dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) exports from island drainage are significant components of total carbon loss and are controlled by land use, hydrology, and discharge volume. These lateral carbon exports further highlight that oxidation-driven subsidence results not only in atmospheric GHG emissions but also in substantial aqueous carbon losses transported into Delta waterway. Additional work by Richardson et al. (2022) expanded this analysis to include nutrients (e.g., nitrate, ammonium, phosphate) and trace elements exported from island drainage. Their findings show that constituent concentrations and fluxes differ markedly among land uses, with subsided agricultural islands acting as hotspots for nutrient and trace-element loading, affecting downstream water quality, biogeochemistry, and ecosystem functioning.

Table 1. Flux towers in the Delta and Suisun Marsh. Start date and end date refers to base data times. Vegetation type abbreviations correspond to the following: CRO – croplands: lands covered with temporary crops followed by harvest and a bare soil period; WET – permanent wetlands: lands with a permanent mixture of water and herbaceous woody vegetation that cover extensive areas in either salt, brackish, or fresh water; GRA – Grasslands: Lands with herbaceous types of cover, trees and shrub cover is less than 10%. Variables listed are not exhaustive for each site. Sites not yet in AmeriFlux do not have a site ID.

Site ID	Name	Veg	Start Year	End Year	Elev. (m)	Variables
US-Bi1	Bouldin Island Alfalfa	CRO	2016	2024	-3	CH4, CO2, Flux CO2, Flux CH4
US-Bi2	Bouldin Island Corn	CRO	2017	2024	-5	CH4, CO2, Flux C, Flux CH4
US-Dmg	Dutch Slough Marsh Gilbert Tract	WET	2021	2024	1	CH4, CO2, Flux C, Flux CH4
US-DS1	Staten Island Corn 1	CRO	2018	2020	-6	CO2, CO2 Mixing Ratio, Flux CO2
US-DS2	Staten Island Corn 2	CRO	2020	2023	-6	CO2, CO2 Mixing Ratio, Flux CO2
US-DS3	Staten Island Rice 1	CRO	2021	2023	-7	CO2, Flux CO2
US-Hsm	Hill Slough Marsh	WET	2021	2023	1	CH4, CO2, Flux CO2, Flux CH4
US-Myb	Mayberry Wetland	WET	2010	2023	-4	CH4, CO2, Flux CO2, Flux CH4
US-Si1	Staten Island Fallow	CRO	2012	2013	-4	CH4, CO2, Flux CO2, Flux CH4
US-Si2	Staten Island Flooded	CRO	2011	2013	-4	CH4, CO2, Flux CO2, Flux CH4
US-Snd	Sherman Island	GRA	2007	2014	-5	CO2, Flux CO2
US-Sne	Sherman Island Restored Wetland	GRA	2016	2020	-5	CH4, CO2, Flux CO2, Flux CH4
US-Snf	Sherman Barn	GRA	2018	2020	-4	CH4, CO2, Flux CO2, Flux CH4
US-Srr	Suisun Marsh - Rush Ranch	WET	2014	2017	8	CH4, CO2, Flux CO2, Flux CH4
US-Tw1	Twitchell Wetland West Pond	WET	2011	2023	-5	CH4, CO2, Flux CO2, Flux CH4
US-Tw2	Twitchell Corn	CRO	2012	2013	-5	CO2, Flux CO2
US-Tw3	Twitchell Alfalfa	CRO	2013	2018	-4	CH4, CO2, Flux CO2, Flux CH4
US-Tw4	Twitchell East End Wetland	WET	2013	2023	-5	CH4, CO2, Flux CO2, Flux CH4

Site ID	Name	Veg	Start Year	End Year	Elev. (m)	Variables
US-Tw5	East Pond Wetland	WET	2018	2020	-5	CH4, CO2, Flux CO2, Flux CH4
US-Twt	Twitchell Island	CRO	2009	2017	-7	CH4, CO2, Flux CO2, Flux CH4
TBD	Webb Rice	CRO	2024	2025	-6	CH4, CO2, Flux CO2, Flux CH4
TBD	Webb Wetland	WET	2024	2025	-5	CH4, CO2, Flux CO2, Flux CH4
TBD	Holland Rice	CRO	2025	2025	1	CH4, CO2, Flux CO2, Flux CH4
TBD	Roberts Rice	CRO	2025	2025	-1	CH4, CO2, Flux CO2, Flux CH4

Variables Explained

CH_4 (methane) and CO_2 (carbon dioxide) refers to the chemical compound itself, while "Flux CH_4" and “Flux CO_2” refers to the rate at which the chemical compound moves into or out of a system, such as from soil into the atmosphere.

Recommendations

A portfolio of analysis and modeling that builds on existing efforts is needed to address key questions related to achieving the benefits of sequestering carbon and minimizing GHG emissions if farmers and other land managers are to effectively fine-tune the management of subsiding lands. In the context of minimizing GHG emissions, there is a need to holistically consider multiple GHGs, i.e., CO_2, CH_4, and N_2O, when managing or restoring wetlands (Stein and Lidstrom, 2024). Important topics to target for improving land management in the near term include:

(1) understanding processes controlling methane and N_2O emission, such as the influence of sulfate concentrations, and how they change over time,
(2) developing approaches for promoting greater rates of accumulation and stabilization of organic carbon in wetland soils (especially those which also limit methane emission), and
(3) developing and improving predictive models that can be used to evaluate land use scenarios. Predictive models, for example, would be useful for evaluating the cross-over point at which sequestration of carbon compensates for GHG production in managed freshwater wetlands (Kroeger et al., 2017).

Addressing these topics will help to promote approaches that enhance carbon sequestration and minimize GHG production for the long term. In addition, insights can result from further data analysis from year-round GHG monitoring programs and continuing improvements in coordination of monitoring efforts. For agroecosystems in the Delta, year-round monitoring will be useful to optimize field practices.

Agricultural Practices in the Delta

Findings

Paludiculture as a Subsidence-Mitigation Strategy

Paludiculture – farming on rewetted peat– can help minimize further loss of peat soils and mitigate subsidence and associated GHG emissions. A key finding is that rice production is currently the best suited and most economical paludiculture option in the Delta. The 2022 Cost of Production Study for rice indicates that supporting private growers in land conversion to rice is more effective than relying on wetland habitat restoration on public lands, particularly due to the large extent of private lands (Leinfelder-Miles et al., 2022). The up-front cost of converting from existing crops to paludiculture, however, is a major risk perceived by farmers. To address this, the Sacramento-San Joaquin Delta Conservancy has funded the Delta Rice Conversion Program to help finance the up-front costs for crop conversion for private farmers. At the same time, the two farmers that presented at the workshop indicated they were more concerned about day-to-day and year-to-year viability of their operations than long-term sustainability benefits. Better understanding of how the short-term economic benefits can work in concert with long-term payoffs could support management decisions. Finally, information about crop conversion needs to be conveyed to both farmers (see recommendation below) and to agencies that could design appropriate incentives and resources for rice conversion or other types of paludiculture.

Agricultural Viability

There are both public and private lands in the Delta that are too difficult to farm because of subsidence and drainage issues. Lands described as wet, non-farmable, and marginally farmable have increased 10-fold over the past three decades, from around 677 acres (274 hectares) in 1984 to 6,919 acres (2,800 hectares) in 2012 (Deverel et al., 2015). While Deverel et al. (2015) identified a substantial increase in non-farmable lands between 1984 and 2012, public comments during the review process suggests that a portion of these lands were converted to wetlands or taken out of production due to non-subsidence-related factors. These distinctions are important when evaluating how subsidence affects agricultural viability.

Feasibility and Constraints of Wetland Conversion

Subsidence of much of non-farmable land may be reversed by conversion to managed wetlands, but there are different opportunities and challenges for both public and private landowners. Private landowners often lack cost-effective approaches for creating managed wetlands and confront regulatory issues. At the time of workshop in 2023, establishing a managed wetland can cost the farmer more than $10,000/acre because of regulation costs (permits, meetings, reporting requirements) and removing land from production. More recent conversations through the public comment process indicate a lower per acre construction cost.

Creating temporary wetlands (i.e., “walking wetlands”, see USFWS, 2024) that may be moved to different locations on the landscape is a strategy to avoid regulatory costs (e.g., permitting, monitoring), which are typically incurred when wetlands are in place for more than three years. These temporary wetlands may also strike the balance between minimizing subsidence and allowing crop rotation, i.e., helping slow the loss of peat soils while regenerating land to increase crop yields. Such strategies are nascent, not well tested in the Delta, and generate a multitude of ecological concerns. Public landowners such as Metropolitan Water District and Department of Water Resources may have more opportunities for demonstrating the long-term benefits of conversion of lands that are too wet to farm to permanently managed wetlands.

Recommendations

Enhance Scientific Design of Incentive Programs Through Expanded Cost-Benefit Analysis

Formal incentives – like the recently funded program for rice cultivation by the Sacramento-San Joaquin Delta Conservancy with The Nature Conservancy – can be further developed to encourage farmers to pursue paludiculture. To determine which incentives are appropriate, **we recommend more comprehensive assessments and modeling of the net benefits of changing production type and the costs and types of financial incentives that motivate Delta farmers to shift to paludiculture and understand the ecological tradeoffs for doing so**. Understanding how such incentives and crop choices provide adequate resources to meet farmer needs is important for creating effective incentives.

Leverage Social Science Research to Improve Knowledge Transfer Among Landowners

Drawing on existing social science, **we recommend incorporating knowledge about the mechanisms for knowledge sharing among farmers/private landowners in the design of incentive programs.** Doing so can help disseminate knowledge about economic and soil sustainability benefits of paludiculture practices in the Delta.

Assess the Scientific and Economic Viability of Alternative Paludiculture Systems

A suggestion from workshop participants of an alternative approach to addressing subsidence was that paludiculture practices other than rice (e.g., raising water buffalo for cheese production) might be economically feasible. However, more data from field efforts within the Delta or other regions could help determine if these practices can be implemented in the Delta. If so, **additional studies would need to**

done to understand both the benefits for avoiding carbon emissions and mitigating subsidence, as well as what types of economic benefits would be created and what financial incentives would motivate producers to adopt other paludiculture practices.

Evaluate Incentive Structures and Regulatory Costs for Wetland Conversion on Deeply Subsided Lands

To address the agricultural challenge posed by land that is too wet to farm, **it is necessary to assess the costs (including regulatory costs) and types of incentives that influence choices to establish managed wetlands on deeply subsided lands.** Agencies and institutions that are already active in these areas and could provide additional leadership include the Sacramento-San Joaquin Delta Conservancy, University of California Cooperative Extension, Delta Science Program/Delta Stewardship Council, the Metropolitan Water District of Southern California, and The Nature Conservancy.

Delta Landscape Challenges

Findings

Landscape Diversity and Landowner Participation in Subsidence Management

The significant regional physical, social, and agricultural differences across the Delta – which has more than 600,000 residents on 738,000 acres (298,658 hectares) of former tidal wetlands that were drained and leveed – provide a great deal of opportunity, yet pose distinct challenges for addressing subsidence across the Delta landscape. For instance, the priorities and interests related to subsidence management of many of the landowners and people across the landscape remain insufficiently characterized. Importantly, the primary factor determining where subsidence-mitigation projects can be sited is the willingness of landowners to participate.

Co-Benefits, Tradeoffs, and Water-Quality Considerations

Likewise, co-benefits (e.g., carbon sequestration, avoided carbon emissions, flood impact mitigation, levee stability, habitat restoration, salinity management) and key tradeoffs (e.g., impacts of water quality and quantity with expanding rice farming relative to current practices) are not adequately quantified or modeled across the Delta. However, some paludiculture practices may introduce additional water-quality tradeoffs. For example, Ackerman et al. (2015) found that mercury concentrations in fish from rice fields were substantially higher than those from restored wetlands, with a majority of sampled fish in rice fields exceeding ecological health benchmarks.

Such knowledge can help inform how to better design targeted management strategies or policy tools that would improve current land-use and farming practices in the Delta. The third panel at the workshop emphasized the growing need for sustained, long-term funding to support landowner incentives. Expanding landowner incentives can increase adoption of subsidence-mitigation practices and, in turn, create more opportunities to establish projects in high-priority scientific study areas where co-benefits and tradeoffs could be evaluated.

Carbon-Market Potential and Implementation Challenges

Given the potential for avoided carbon emissions as a co-benefit of inundating subsided Delta lands, there has been growing interest in how current carbon markets can be used to expand financial incentives for wetland restoration, paludiculture, and other rewetting practices. A large partnership of agencies and academics developed the “Restoration of the California Deltaic and Coastal Wetlands” methodology (ACR, 2017), which was adopted in 2017 by the American Carbon Registry. It allows verified projects to receive carbon credits for avoided carbon emissions. Currently, carbon credits can be registered on the voluntary carbon market, generating financial incentives for land use conversion to wetlands and paludiculture. The approved, peer-reviewed ACR methodology includes explicit accounting procedures for CO_2, CH_4, and N_2O, incorporating conservative and scientifically vetted GHG factors for climate accounting.

Through this program, the California Department of Water Resources has established wetland projects on Twitchell Island and Sherman Island that have received credits for avoiding carbon emissions from 2015 to 2018. In 2025, the California Department of Water Resources certified approximately 110,000 credits under this methodology and has been quoted a market price of ~$30 to $40 per credit, representing a potential ~$3.3 to $4.4 million in revenue. Credits are being evaluated for projects on Staten Island and Webb Tract. If deemed feasible, the protocol could be adopted by the Air Resources Board under California’s Cap-and-Trade compliance market, which would increase the value of each credit.

Despite growing interest and recent progress, a number of structural barriers continue to constrain the feasibility of using carbon markets and rewetting strategies to manage subsidence across the Delta. First, participation in the voluntary carbon market requires a 40-year contract, and the compliance market requires a 100-year contract (Deverel et al., 2017). Such contract lengths can be difficult for potential participants, particularly farmers, who must deal with the reality of generating income from these lands over the short term.

Second, although the ACR protocol uses approved and peer-reviewed methods for quantifying CH_4 and N_2O emissions, scientific uncertainty remains about long-term GHG flux trajectories across different rewetting strategies. Managed wetlands, rice cultivation, and tidal reconnection each produce different balances of CO_2 uptake, CH_4 emissions, and N_2O fluxes, and the tipping point at which carbon sequestration outweighs methane's warming effect varies by land-use type. Consequently, additional research is needed to refine GHG emission factors and reduce uncertainty in predictive models supporting carbon-market verification.

Third, changes to policies, such as Assembly Bill 1757 (the California Global Warming Solutions Act of 2006), which addresses GHG emissions from working lands, potentially have implications for how the Delta landscape will be managed, but assessments of the implications of such policy changes are lacking. As mandated by AB 1757, the State of California has released a strategy aiming to rewet roughly 50,000 acres (20,234 hectares) of Delta peat soils by 2045 (CNRA 2024). This ambitious goal, which can be achieved through agricultural practices or habitat restoration, relies heavily on widespread adoption of climate-friendly methods like rice cultivation and paludiculture by private landowners, who own most of the Delta's land.

While obstacles remain, such as the cost and complexity of validation, long contract lengths, and the need for predictable GHG accounting, the current characterization of carbon-market economics must recognize rapidly improving financial feasibility. Carbon-credit prices for Delta projects have risen substantially, and the cost of verification is decreasing as programs mature. This momentum increases the potential for carbon markets to become a meaningful incentive mechanism for land-use conversion.

In addition to these technical and economic considerations, several equity and social-impact questions related to carbon-market expansion in the Delta warrant further attention. Public comments noted that carbon-credit development may compete with existing land uses, and benefits from carbon revenues may not be evenly distributed across Delta communities or Tribes. Long-term contracts that transfer carbon rights to third-party developers, often at relatively low initial prices, may also expose farmers and landowners to future financial risk if credit values rise, raising questions about who ultimately bears that risk. These concerns highlight the need to evaluate carbon-market participation not only as a climate-finance mechanism, but also through a broader environmental-justice lens that considers community priorities, landowner autonomy, and how carbon-credit revenues might support Delta-as-Place values beyond subsidence mitigation.

Recommendations

The Delta ISB recommends continuing to quantify and refine knowledge of the effects and tradeoffs of different public and private incentives for inundating Delta lands and how such outcomes are aligned with the priorities and values of the diverse communities, including Tribes, and landowners in the Delta. This information will provide essential, practical support to inform and adapt policies promoting changes in land use and management across the diverse Delta landscape. Central to this is understanding of the impact of different management practices, e.g., crop rotation, soil wetting and drying, on subsidence rates and net GHG emissions and on carbon sequestration across the Delta landscape. Further, the degree to which such changes support ecological benefits, levee stability, and economic health of Delta communities will be quantified as well.

Advancing scientific understanding of the underlying biogeochemical processes that influence net GHG emission associated with alternative landscape scenarios is a high priority for informing the extent to which carbon markets and credit verification requirements can effectively motivate changes in landscape practices; ones that will mitigate subsidence while also reducing GHG emissions. This expanded knowledge will yield several practical benefits. For example, it will improve the accuracy and reliability of carbon-market accounting, clarify when and where rewetting strategies produce net climate benefits, and help agencies adapt carbon-market policies to lower compliance and verification costs for landowners.

Next Steps: Building off Current Momentum

In summary, the review found that managed wetland restoration, rice cultivation, and floating tule wetlands can help slow or reverse subsidence in areas of the Delta while generating co-benefits such as carbon sequestration, habitat restoration, and potential economic opportunities for farmers when shifting to rice production. To build on these lessons, the Delta ISB recommends establishing a strategic long-term program to coordinate, track outcomes of projects and to align priorities. With current projects underway and new projects coming up, there is an opportunity to improve understanding of the rates of methane and nitrous oxide emission with different management practices, and the effects and tradeoffs of different public and private incentives for inundating Delta land. The Delta has a strong scientific foundation and regional expertise to advance subsidence research and land management practices moving forward.

Momentum across the Delta community to respond to and advance the Delta ISB's recommendations grew rapidly, as this report was being finalized, reflecting both shared urgency and strong regional commitment to addressing subsidence. As the Delta ISB conducted this review, the Sacramento–San Joaquin Delta Conservancy secured a $36 million General Fund allocation in 2022 that enabled four landscape-scale pilot projects, totaling 5,500 acres (2,226 hectares) of rice and 3,423 acres (1,385 hectares) of wetlands. These subsidence reversal projects included the Webb Tract Rice/Wetland Mosaic and the Delta Rice Incentive Program. As the Delta ISB review was underway, the Delta Conservancy incorporated lessons learned from the Delta ISB workshop into these projects, and highlighted this integration in its January 2026 presentation to the Delta ISB.

Recognizing the need for coordinated leadership and leveraging the momentum of the Delta ISB review, the Delta Conservancy and The Nature Conservancy formed Delta Carbon Team in March 2025, to advance the implementation of subsidence and emission reducing projects in the Delta. As highlighted in the presentation to the Delta ISB in January 2026, a lot of the planned work of the Delta Carbon Team can address the Delta ISB recommendations.

Through it comments to the Delta ISB, District 10 of the California Department of Transportation (Caltrans) has expressed support for the scientific efforts that reduce greenhouse-gas emissions through carbon sequestration and wetland management, and for sustainable land-use practices that help mitigate the effects of sea-level rise and subsidence in the Delta. Caltrans District 10 hopes to advance cross-agency collaboration and promote the use of emerging monitoring technologies that protect transportation infrastructure and maintain safe travel corridors for the communities that depend on Delta roadways.

At the same time, the Delta Stewardship Council used insights from the review to shape climate-adaptation strategies in Delta Adapts, including exploring options to streamline and reduce the costs of developing and listing carbon credits (DSC 2025). In addition, the Council highlighted key research gaps in wetland GHG biogeochemistry for inclusion in the upcoming regional synthesis report for the Delta, as part of California's Fifth Climate Change Assessment.

Complementing these efforts, the Delta Science Program funded new work in 2025 to assemble and analyze recent Delta data, including land-surface elevation, GHG fluxes, soil organic matter, depth-to-groundwater, and peat thickness, to refine and recalibrate the SUBCALC model and strengthen decadal-scale subsidence forecasting (Delta Science Program 2025). The SUBCALC model is a tool that estimates subsidence rates and CO_2 emissions, aiding carbon offset validation and land-use decisions. This funded project addresses both the Delta ISB recommendations and Action 3D of the 2022-2026 Science Action Agenda (DSC 2022). This highlights how addressing Delta ISB recommendations can also address community needs identified in the Science Action Agenda. Altogether, these coordinated actions demonstrate substantial and accelerating progress toward implementing the Delta ISB's recommendations, with further advancements still possible as agencies continue to expand and refine their efforts.

Building on the insights from this review, the Delta ISB decided to scope a broader evaluation of nature-based solutions, which will also encompass subsidence-reversal projects. A recent panel discussion in May 2026 with State agency leaders underscored both the importance and the difficulty of quantifying co-benefits, an issue flagged in this review and one that the forthcoming ISB effort is hoping to further explore.

Part 2: Context for Understanding the Findings and Recommendations

Overview of Delta Subsidence and its Impacts

Subsidence in the Delta represents a major, system-scale challenge with implications for greenhouse-gas emissions, water supply reliability, levee performance, Delta communities, and the long-term viability of Delta agriculture. Land subsidence may also contribute to historic and recurring flooding that inundates drainage systems along State Routes in the Delta, as described from public comments from Caltrans, illustrating how declining ground elevation affects critical transportation infrastructure.

At the same time, multiple ongoing projects, implemented by State agencies, regional entities, NGOs, and local landowners, have shown that land-use changes such as wetlands, rice, and rewetting can reduce subsidence and lower net greenhouse-gas emissions. Scientific understanding of Delta subsidence processes has advanced substantially over the past two decades, providing a strong foundation for evaluating and scaling mitigation approaches.

Before the surge in human migration to California in the mid-1800's, the Sacramento-San Joaquin Delta was the largest freshwater estuarine wetland on the west coast of North America (SFEI, 2022). In the 6,700 years that the estuarine wetland has existed, it was a major sink for carbon as the wetland plants turned into peat as they were buried by new plant growth and riverine sediment. This long-term burial created a major carbon sink, storing an estimated 288 million metric tons of carbon in the undisturbed Delta (Vaughn et al., 2024). Although large-scale reclamation accelerated in the 1880s with the advent of clamshell dredges, levee construction and drainage efforts had already begun decades earlier.

Historical accounts, such as Thompson (1957), indicate that reclamation activities were underway by the 1850s, with Union and Grand Island designated as reclamation districts in the early 1860s. These early efforts set the stage for the more intensive transformation of the Delta landscape that followed later in the century. Reclamation of the wetlands continued until the 1930's when most of the islands had been reclaimed by building levees and draining. The reclaimed islands yielded some of the most productive farmland in California because of the rich organic soil and nearby access to irrigation water.

An important aspect of agricultural cultivation in organic soil is that the chemical environmental changes when the soil is drained to desaturate the root zone to cultivate crops (Stephens et al., 1984). The chemical environment of the soil is fundamentally altered from an anaerobic (no oxygen) condition in the undisturbed natural wetland to an aerobic (oxygen rich) condition in the drained cultivated areas. This promotes microbial oxidation of organic matter (e.g., decomposition) in the drained organic soil and generation of carbon dioxide. Vaughn et al. (2024) found that historical peat deposits totaled approximately 7.8 billion cubic meters, which is roughly the volume of 7,800 football stadiums. They estimate that two-thirds of this original peat volume has now disappeared, primarily through microbial oxidation and compaction under drained conditions.

The loss of organic soil in the Delta is significant from both landscape and climate perspectives. Land subsidence is the most visible landscape consequence from the oxidation of organic material. Most Delta islands now lie below sea level and require an extensive levee system to protect them from flooding. The climate impact is more subtle because it is caused by the carbon dioxide generated by the oxidation of soil organic matter. Carbon dioxide is a major greenhouse gas generated by human activity and a contributor to global warming.

Most of the Delta has experienced subsidence. The subsidence is spatially variable but greatest in areas where organic soils were thickest, particularly the central and western Delta. Deverel et al. (2020) estimate that 247,000 acres (~99,957 hectares) of land in the Delta have subsided from ~-10 to -30 feet (~-3 to -9 meters). Of this total, ~150,000 acres (~60,703 hectares) are considered deeply subsided (below -16 feet or -5 meters).

While the locally large magnitudes of subsidence are indicative of its impact, the volume of land area in the Delta that lies below sea level is a better measure of the potential regional impact of subsidence (Mount and Twiss, 2005). This volume, which is referred to as “anthropogenic accommodation space”, quantifies the severity of the flooding potential in the Delta. Mount and Twiss (2005) estimate that the increase in accommodation space from subsidence during the twentieth century was 8.8×10^{10} cubic feet (2.5×10^{9} cubic meters), which can roughly fill 2,500 football stadiums. By 2050, they estimate from subsidence projections that the accommodation space will increase to 10.6×10^{10} cubic feet (3×10^{9} cubic meters), an increase of 20% or 500 football stadiums. The implication of this trend of increasing accommodation space is much greater impact when islands flood and change the hydrology and hydrodynamics of water movement, salinity intrusion, and costs, including time and money, to reclaim a flooded island.

The climatic impact from GHG emissions from the Delta would be significant if subsidence were to continue. SFEI (2022) estimates that if all remaining organic soil matter in the Delta were oxidized, it would generate 154 million tons (140 million metric tons) of carbon dioxide. This is equivalent to clear-cutting more than 3.5 million acres of forest or burning half a trillion pounds of coal. Currently, State-wide agriculture generates 8% of California's total GHG emissions. Deverel et al. (2020), estimate that the Delta alone currently generates 6% of California's total agricultural emissions and 21% of its non-animal agricultural emissions. These statistics underscore how a relatively small portion of California's farmland, specifically the peat-soil islands of the Delta, contributes a disproportionately large share of emissions due to subsidence-driven peat oxidation, reinforcing the importance of reducing these emissions. Thus, although it is unlikely that all remaining organic soil will be oxidized, reversing, arresting, or slowing subsidence in the Delta would contribute to meeting State-wide GHG emission reduction goals.

Managing Subsided Lands Workshop Summary

The primary input to this review was a two-day public workshop structured as four half-day panel presentations and public discussions on managing subsided lands in the Delta (see day 1 recording and day 2 recording). Each panel consisted of three to four experts (see agenda). Following brief presentations by the invited experts, a lengthy public discussion was led by a Delta ISB member. Panelists were invited by the Delta ISB to provide perspectives on existing programs, barriers and opportunities, state of scientific understanding, scientific gaps and deficiencies, and economic considerations of managing subsided lands. The following subject matter was addressed by the four panels:

1. Overview of current land inundation practices and experiments
2. Biogeochemistry of carbon sequestration and greenhouse gas emissions in inundated organic soils
3. Economic considerations for inundated agricultural practices
4. Science needs to inform landscape-scale implications of organic soil inundation.

The first panel focused on understanding the scope of current inundation projects in the Delta, with an emphasis on land surface elevation changes. The second panel discussed the biogeochemical mechanisms that regulate greenhouse gas emissions and sequestration in wetland organic soils, noting gaps in scientific understanding. The third panel addressed different agricultural and land-use management practices to identify the opportunities and barriers for paludiculture or other inundation practices and the possible trade-offs in agricultural practices for managing subsided lands. The fourth panel reflected on the previous three panels and explored research and data needs to understand potential landscape-scale implications of soil inundation.

The summaries of the workshop are based on what panelists presented, and references were added when those sources were cited in the presentation slides. Each panelist had the opportunity to review and confirm the accuracy of the write-up for their portion of the workshop, including verifying and adding references. New research has come out since the workshop, but this section summarizes what was known and discussed at that time. The findings and recommendations provided earlier in the report incorporates the new information that emerged after the workshop.

Panel 1: Overview of Current Land Inundation Practices and Experiments

Steve Deverel | A Whale of a Tale: Subsidence, Effects and Solutions

Pre-development, the Delta was a vast emergent tidal wetland ecosystem that accumulated an estimated 275 billion cubic feet (7.8 billion cubic meters) of rich peat soils over the last 6,000 years (Vaughn et al., 2024). Drainage and exposure of peat soils to oxygen since the 1860’s has led to the loss of an estimated two thirds of the historical peat volume (Vaughn et al., 2024), which resulted in subsidence (Mount and Twiss, 2005). Sea level rise progressed rapidly until about 6,000 years ago when it slowed to an annual rate of about 1/16 of an inch (1.7 millimeters) upon reaching the Delta (Atwater, 1980). Historically, wetland accretion was sufficient to maintain elevations concomitant with sea level rise (Deverel et al. 2014).

Microbial oxidation of the organic matter in Delta organic soils is the primary cause of subsidence (Deverel and Leighton, 2010). In the central Delta, where subsidence is the most severe, land elevations have decreased to more than 20 feet below sea level. Elevation surveys conducted by University of California researchers across Bacon, Lower Jones, and Mildred Islands starting in the 1920s demonstrated that rates of subsidence decreased with time. On Bacon Island, subsidence rates were 2.6 inches (6.6 centimeters) per year prior to 1960 due to high soil organic matter content and declined to about 1.2 inches (3 centimeters) per year as soil organic matter content decreased due to oxidation (Deverel and Leighton, 2010).

Subsidence rates are directly linked to organic matter content; worldwide subsidence rates are higher in soils with higher organic matter content (Deverel and Leighton, 2010; Stephens et al., 1984). Subsidence rates have long been known to be directly correlated with depth to groundwater and temperature (Stephens et al., 1984).

Important consequences of subsidence are levee failure and island flooding. The Brannan-Andrus Island breach in 1972 is an important example, as it prompted State investment in levees and investigation of subsidence. During this event, salinity levels in the Delta increased 2.5 to 4-fold, which resulted in the shutdown of the State Water Project, and the release of 300,000-acre feet of water to return salinity concentrations to pre-breach levels. In today's dollars, the total cost would be an estimated $150 million. Since 1973, repairs, upgrades and maintenance for the Delta levees totaled almost a billion dollars.

Geoslope modeling indicated a correlation between organic soil thickness and the relative probability of levee failure (Deverel et al., 2016a). As oxidation decreases peat thickness, seepage forces exponentially increase, particularly where peat thickness is less than 9.8 feet (3.0 meters). Seepage forces have the potential to erode levee foundation materials. This erosion process can result in boils in toe ditches such as the one observed on Jones Tract (see Figure 6), which are an indication of eroding levee foundations.

Figure 6. Active boil on Jones Tract observed in 2011. Photo credit: Gerald Bawden

Paludiculture and establishing permanently flooded non-tidal (impounded) wetland have been shown to stop and reverse the effects of subsidence in the case of wetlands. Sediment elevation (erosion) table measurements in the Twitchell Island West Pond wetland from 1997 to 2017 indicate an average accretion rate of 1.2 inches (3 centimeters) year^{-1} (Deverel et al., 2020). Sediment erosion table measurements on a rice field on Staten Island indicate that paludiculture can stop subsidence. Accumulation of senescent biomass in the Twitchell West Pond wetland may be inhibiting nascent growth and carbon sequestration.

Impounded wetlands may benefit from more active management to remove senescent biomass to ensure that new growth can continue for carbon sequestration benefits. Managing water levels in impounded wetlands to be commensurate with wetland accretion is also essential to promoting increases in land surface elevations. This concept was instilled during the construction and management of the Twitchell West and East Pond wetlands based on concepts presented in Callaway et al. (1996).

Land-use mosaic experiments are underway to evaluate options to provide both income to maintain levees and mitigate subsidence and reduce greenhouse gas emissions (Deverel et al., 2017). On Staten Island, rice and wetlands are being implemented in the most subsided areas to reduce and reverse subsidence and reduce greenhouse gas emissions and generate income, while more traditional crops such as corn are grown in areas of the island with less subsidence.

The overarching challenge is to implement subsidence mitigation practices on a landscape-scale. This is a complex, interdisciplinary issue, and there is a need to prioritize raising the land-surface elevation in areas where it can meaningfully reduce the probability of levee failure over time. There are knowledge gaps in how to manage these land uses to achieve other benefits such as increasing food web benefits and increasing carbon sequestration, particularly while accounting for methane emissions. These include the following:

- There are no data on how compaction of the accreting organic matter affects the long-term increase in elevation in the Delta, which makes it difficult to model accretion in impounded freshwater wetlands in the Delta over the long-term.
- Paludiculture, the practice of harvesting wetland biomass to generate income, is practiced in Europe and Canada. This practice could be a promising avenue for the Delta, particularly considering the large amounts of biomass available in impounded wetlands. Experimental plots are needed in the Delta to assess its viability.
- The carbon-market protocol requiring 40-year commitment to paludiculture can be challenging for farmers, and there is a need to examine if it is compatible with crop rotation, particularly while accounting for methane.

- Quantifying the spatial variability of present-day subsidence rates in the Delta can be useful to prioritizing areas for alternate land use although it can be challenging. More accurate techniques to quantify spatial variability of subsidence would be useful.

Gilbert Cosio | How Subsidence Affects Reclamation Districts

Subsidence impacts agriculture by affecting drainage characteristics of the landscape. LiDAR elevation maps indicate high spatial variability of subsidence (Figure 7), creating steep elevation differences where one part of the island can be over 12.0 feet (3.7 meters) lower than the rest. Therefore, lower lying areas that have lost substantial amounts of peat and elevation are increasingly difficult to drain for farming. Simultaneously, the loss of peat, which is less permeable than the underlying sand, can cause sand boils to develop. Boils form when the high hydrostatic head of water on the water-channel side of the levee causes water to flow beneath the levee at a velocity that erodes sandy subsoil, effectively creating quicksand. For example, on Grand Island, active boils in drainage ditches have forced abandoning acres of farmland that can no longer be drained to support agriculture. Although drainage ditches could be widened, this carries a risk of de-stabilizing levee foundations as seepage will erode sand from levee foundations.

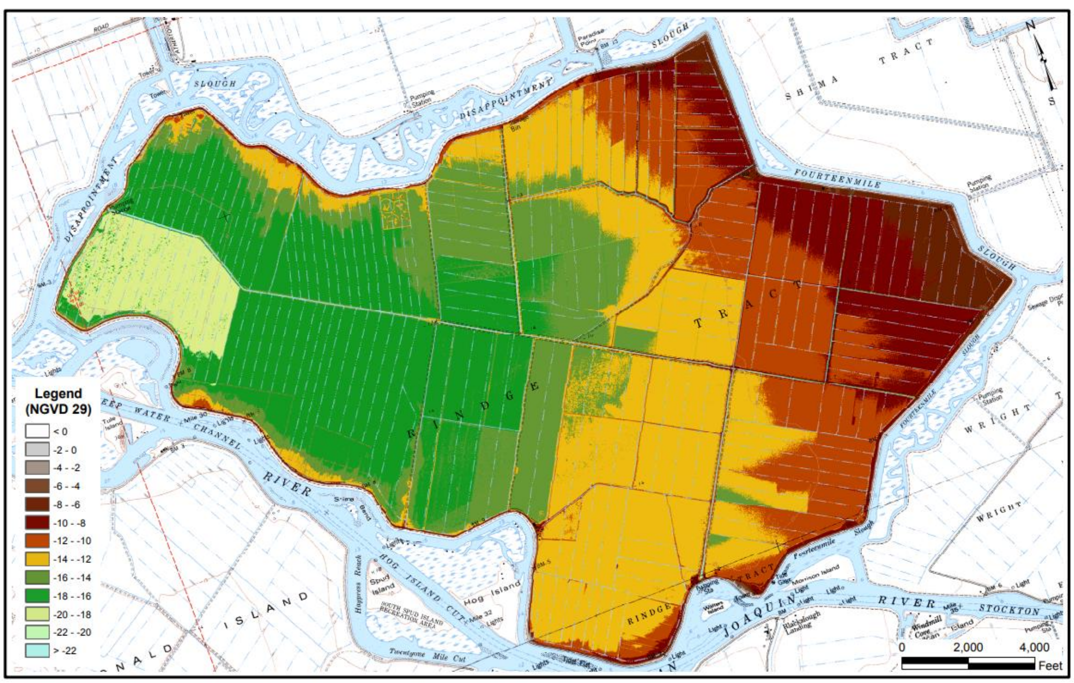


Figure 7. Slide from Gilbert Cosio's presentation on subsidence in reclamation districts. Map depicts Rindge Tract LiDAR data

Subsidence creates a risk for levee failure when the loss of peat, which prevents saturation of the underlying sand, allows water to run through a levee. As peat is lost, sand is increasingly saturated, which causes a loss of cohesion and strength in levee foundations. In some areas, subsidence has been so severe that water has moved upward through the sand and is pooling on top. Levee failure carries major consequences for roads and other types of critical infrastructure, which highlights the importance of reversing subsidence in areas where drainage systems are stressed and where peat has thinned above the underlying sand.

Many studies in the 1980s from academics, district engineers, the U.S. Army Corps of Engineers, and the California Department of Water Resources focused on the “zone of influence” (the stretch of land ~500 feet (152 meters) from the levee on the land side) and levee stability. A key outcome of these studies was that reversing subsidence in the zone of influence could significantly improve levee stability. Initiatives such as Senate Bill 34, which allowed the purchase of conservation easements for the zone of influence, were created to prevent farming in the zone. However, this incentive was too costly for farmers, landowners, and other rights holders who also had to consider the cost to maintain the levees. Ultimately, being aware of the location of subsidence and depth to groundwater and having familiarity with the levee system can help identify issues that affect levee stability.

Russ Ryan | Managing Subsided Lands in the Sacramento-San Joaquin Delta

The decline in land elevation due to peat oxidation increases levee vulnerability to hydrostatic pressure and seepage. Changes in hydrology, such as king tides and flood events, can raise water levels, which increase hydrostatic pressure even more. Similarly, seepage, which is net flow under the levee, is proportional to the thickness of the levee. In addition, sea level rise worsens the risk that levees may no longer be adequate to prevent overtopping and flooding. To address these risks, the Metropolitan Water District of Southern California (hereafter, Metropolitan) is conducting research on four islands (Webb Tract, Holland Tract, Bacon Island, and Bouldin Island) in the Delta to control subsidence in a project collectively known as the Delta Islands Landscape Collaboration.

Metropolitan’s Delta Islands Landscape Collaboration is funded through a 2020 California Department of Fish and Wildlife Prop 1 Watershed Restoration Grant. The goal is to identify opportunities for ecosystem enhancements, water supply improvements, carbon sequestration, and subsidence control on Metropolitan’s four islands. A key aspect of the project is building community partnerships to plan future multi-benefit restoration projects.

For example, one pilot project on Bouldin Island was focused on growing tules in free-floating containment areas experiencing different flow regimes (e.g., similar to more open river-like flows). These containment areas simulated the influence of flow regimes on residence times. As tules grew and their root structures developed, researchers found increasing concentrations of fish food, i.e. zooplankton. Metropolitan is in the process of expanding this experiment, and developing floating tule mats, on a larger pond to evaluate benefits for fish.

David Julian | Sherman and Twitchell Island Subsidence Reversal and Carbon Sequestration

Over the last two decades, the California Department of Water Resources has conducted different projects with many partners for subsidence reversal and carbon sequestration under the West Delta Program managed by the Division of Multi-Benefit Initiatives with funding from State Water Project.

The West Delta Program operates primarily on Sherman and Twitchell Islands where the California Department of Water Resources owns approximately 80% of each island. The majority of Sherman and Twitchell Islands were purchased by California Department of Water Resources in the 1990s, in response to Decision 1641 (D-1641), to set water quality baselines further upstream in the Delta and to ensure reliable water quality for the State Water Project exports. As the western-most islands in the Delta, Sherman and Twitchell effectively act as a barrier against salt-water intrusion which would compromise water quality. In recognition that subsidence could impact the integrity of Sherman and Twitchell Islands, the California Department of Water Resources began early experiments to address subsidence and provide wildlife habitat.

Currently, Sherman and Twitchell Islands are about 15 to 20 feet below sea level, with accommodation spaces (volume of water that will flood the island if levees fail) of 140,000 acre-feet and 55,700 acre-feet respectively. As subsidence progresses, accommodation space increases. The California Department of Water Resources has pursued and initiated different projects to decrease the impact of subsidence on Sherman and Twitchell Islands (Table 2). The primary goals for these wetland projects are to reverse subsidence and to sequester carbon. Currently, the field projects are observing rates of 0.75 to 1.5 inches (2.0 to 4.0 centimeters) of soil accretion per year and about 10 tons of CO_2 equivalent greenhouse gas reduction per acre per year, compared to previous land uses, in wetland projects.

The Twitchell Rice Project evaluated the potential for rice to reverse subsidence while providing income. They observed that planting rice resulted in about 0 to 0.4 inches (0 to 1 centimeter) of organic soil accretion per year, which halts subsidence although not as much as impounding wetlands. Rice production reduced greenhouse gas emissions, compared to previous land uses, by 7 tons of CO_2 equivalent per acre per year which was also less than greenhouse gas reductions from wetlands. While planting rice did generate more profit than wetlands, growing rice requires monetary subsidies to be profitable. However, rice also has an added benefit of providing migratory waterfowl habitat when the fields are flooded in the fall.

Table 2. West Delta Program projects and acreage.

Year	Name	Acres
1997	USGS Wetland	14
2010	Mayberry Farms	315
2010	Twitchell Rice Project	588
2013	East End	750
2016	Whale’s Mouth	650
2022	Whale’s Belly	1000

In total, the California Department of Water Resources has constructed close to 3,000 acres (1,214 hectare) of wetlands and 500 acres (202 hectare) of rice in the most subsided areas of Sherman and Twitchell (Table 2). Construction for these projects was based on opportunistic funding. Key considerations going forward are managing salinity concentrations, water depth, vector control, and vegetation. Different management actions for these considerations are required on different parts of the islands.

The California Department of Water Resources is among the first to register carbon credits to participate in the voluntary carbon market. The California Department of Water Resources helped to develop the American Carbon Registry carbon offset protocol for the region, and they have 52,000 carbon credits registered (Deverel et al., 2017). However, they are not currently being used, and the process is still under development for implementation.

Cathleen Jones | Remote Sensing of Levees and Land Subsidence

The value of remote sensing is the ability to gather a snapshot of an entire landscape at once. Remote sensing approaches facilitate consistent monitoring across different areas, including sites that are difficult to access, to observe subtle changes in water, soil moisture, and ground level. In addition to measuring changes in surface position, in principle, remote sensing could be applied to evaluate seepage in Delta levees.

High heterogeneity of levee conditions across the Delta makes it difficult to extrapolate findings from one spot on one island to the potential seeps, cracks, instabilities, and subsidence conditions across the entire Delta levee system. Increasing remote sensing capabilities could allow for more effective monitoring of the connection between subsidence and levee stability.

Geodesy refers to the technology that measures the position of different points on Earth and the ground. Examples of different geodetic technologies include total station surveys, extensometers, and ground-based LiDAR surveys. There are also remote sensing methods such as Global Positioning System (GPS) and Global Navigation Satellite System (GNSS), which are based on measurements at single point locations, but are more accurate and measure continuously through time. Ground-based methods are essential for validating other remote sensing methods that occur at larger scales such as interferometric synthetic aperture radar (InSAR).

InSAR images an entire area at one point in time by transmitting radar signals from instruments on high-flying aircraft or satellites and measuring the timing between when the radar signal is transmitted and when the reflection from the ground returns to the instrument. It is used to measure changes in the surface, including changes in surface elevation. Repeat measurements over the same area over time reveal even very small changes in the land surface.

Experiments conducted in 2008 using an airborne instrument to examine levees found enormous signals, amounting to centimeters of movement in a short amount of time, on the Sherman Island levee (Sharma et al., 2016). Subsequent site visits confirmed the presence of a crack in the levee that would not have been easily noticeable. However, it is very clearly visible in INSAR data (Figure 8).

The National Aeronautics and Space Administration (NASA) is launching a mission in spring 2024 called the NASA-ISRO synthetic aperture radar (NISAR) that will carry an instrument that is well-suited for measuring subsidence. This mission will measure every part of California twice every 12 days continuously for several years. The mission lifetime is nominally three years, but the spacecraft carries sufficient fuel to operate for more than 10 years; so, barring instrument failure, it is expected to operate far longer than the nominal lifetime. An important contribution of this mission is that all the data products will be free and openly available to the public.

The NISAR mission addresses a major barrier, the cost of geodesy data, inhibiting remote sensing applications in the Delta. However, now the main barrier will be understanding the technology to be able to use it. Adding more GPS (global position system) stations at locations in the Delta will improve the calibration of measurements from NISAR and other similar remote sensing measurements, providing robust measurements to support operational monitoring of surface elevation change.

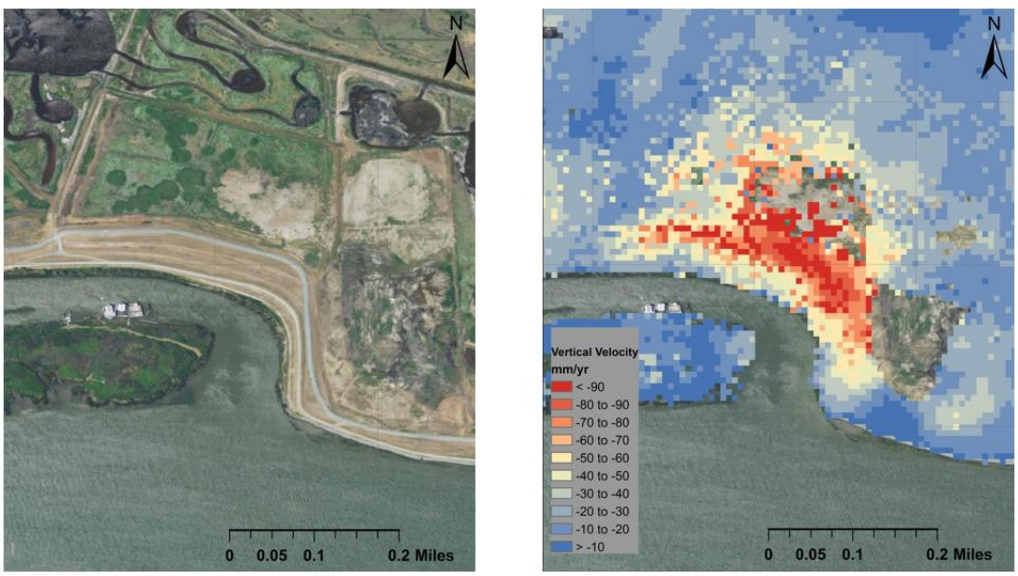


Figure 8. INSAR data of a Sherman Island levee taken from Dr. Cathleen Jone's presentation.

Panel 1 Discussion Summary

Subsidence, sea level rise, and seismic activity are compounding hazards to the Delta, particularly because these threaten levee structures. Management actions to reduce subsidence, such as floating wetlands, and converting land use into permanent freshwater wetlands or paludiculture, may have the added benefit of decreasing susceptibility to sea level rise. However, management actions have trade-offs. It will be important to consider the design of projects to maximize benefits for multiple objectives such as reversing subsidence and maintaining water supply reliability. For example, reducing subsidence requires inundating soil, yet future projections predict declining water supplies. Future managers will need tools to evaluate how to balance water management to minimize subsidence, greenhouse gases, and support carbon sequestration efforts, which will be particularly challenging in drought conditions. A significant impediment to applying approaches such as hazard mapping to better understand risks of different tradeoffs is the availability of data and instruments.

Current rates of subsidence threaten the viability of farming across the Delta. Solutions range from creating wetlands on areas that are already too wet to farm to promoting crops, such as rice or tules, that thrive in inundated soils. One important caveat is that actions that reduce subsidence may increase methane emissions. Methane accounting and methane management is crucial. Managing the refreshment rate of sulfate may help with reducing methane emissions since sulfate inhibits methanogenesis. Water temperature and salinity are major controls on methane emission. If these two factors increase in the future, methane emissions will be impacted. A major uncertainty is the impact of different management actions on balancing greenhouse gas emissions.

For farmers, the regulatory landscape of emissions is a source of frustration. Farming has been exempted from carbon emissions, but changes in regulations might mean that farmers will have to account for emissions. Changing emissions standards means that farmers are asking whether it is worth it to buy new equipment as opposed to renting equipment because of concerns that they will be investing in equipment that might become obsolete.

Proposed solutions need to consider the way that incentives are designed, practice issues with implementation, and their impact on the economic sustainability of farmers and private landowners. Recent protocols that award carbon credits for wetland conversion or rice cultivation can facilitate participation in the voluntary carbon market. The California Air Resources Board (CARB) should consider accepting the American Carbon Registry (ACR) carbon offset methodology for the Delta in order to sell carbon credits as part of the compliance market as opposed to the voluntary market. Carbon credits in the compliance market have been steadily rising. However, CARB will not accept the ACR methodology until there are enough projects, which means that until then, participants using this methodology for carbon offsets can only trade on the lower priced, voluntary market. Though the voluntary carbon market has historically priced carbon credits significantly lower than the per-acre revenues from farm crops, recent developments suggest prices may climb much higher.

Uncertainties in regulations create barriers to farmer and landowner participation. Other mechanisms such as establishing conservation easements may reduce funding hurdles for landowners interested in exploring other revenue options for land that has already subsided too much to remain viable for typical Delta crops. Developing testing sites, examples, and opportunities that account for economic considerations are needed to design effective incentives and support the economic sustainability of the region. The Staten Island mosaic could be an example and, if the economics works out, could be a model for agriculture in a future Delta. Ultimately, the land mosaic would need to be economically profitable to incentivize reducing subsidence.

Rice has been proposed as an alternative crop to replace corn because it can be grown in saturated soils and has a viable and active market. Rice yields in the Delta are already comparable with the Sacramento Valley. However, there are practical challenges to implementing large scale rice cultivation such as concerns with prices and steep upfront costs for leveling land and equipment. Converting land to rice production or wetlands is not as much of a problem as acquiring the funding to do it. However, the sources of funding available to public landowners is inaccessible to private landowners.

Other inundated land purposes such as walking wetlands and raising water buffalo for dairy products were also discussed as methods to promote the management of subsided lands while maintaining profit. However, lower flows in future conditions may affect the availability of water for inundation, increasing the amount of soil exposed, and, subsequently, microbial oxidation. A better understanding of adequate water levels to minimize oxidation and water use will be important to evaluate the viability of different management actions and the associated trade-offs among different land uses on subsidence, particularly with respect to levee maintenance costs.

Panel 2: Biogeochemistry of carbon sequestration and greenhouse gas emissions in inundated peat soils

The Delta is 0.5% of California's agricultural land, but accounts for 6% of total agricultural greenhouse gas emissions, and 21% of non-animal agricultural emissions (Deverel et al., 2020). Subsidence contributes to GHG emissions because CO_2 is released as aerobic microbes consume carbon in the soil. Understanding biogeochemistry is essential for addressing subsidence. Models can be used to evaluate some of the uncertainties by projecting the future impacts of management actions and comprise an important tool.

Lisamarie Windham-Myers | Putting Delta Subsidence Mitigations in a Carbon, Climate, and Coastal Context

A substantial amount of land elevation and carbon have been lost. About half of the carbon, approximately 9.9 x 10^7 tons (90 Teragrams), in Delta soils has been lost since the 1800s (Drexler et al., 2019), resulting in massive greenhouse gas emissions. This amount is roughly equivalent to the carbon contained in more than 300 million mature trees or the annual emissions of over 70 million passenger vehicles. In the central Delta, where subsidence is most severe, the pressure on levees is expected to be much higher than in less subsided areas. Therefore, reducing subsidence is essential to meaningfully address the carbon goals of the state.

In terms of long-term storage, carbon stored in coastal soils and sediments is ideal because there is no saturation limit. Continual sedimentation and biomass accumulation of senescent wetland plant material buries the carbon deeper and deeper as more is captured on the surface. The Delta has high carbon fluxes and productivity, resulting in high carbon density. Per unit volume, the amount of carbon in Delta soils is about 40% higher than the average for other wetlands in the United States. One issue is that sea level rise may threaten wetland ecosystems if water levels drown wetland vegetation. Models like the Marsh Equilibrium Model project coastal carbon storage by factoring in sea level rise.

The Delta is naturally a strong carbon sink (Windham-Myers et al., 2023). However, methane is a potential concern because it can affect net greenhouse gas emissions. The presence of sulfate in the system has been shown to reduce rates of methane emissions (Windham-Myers et al., 2018a). At half-strength concentrations of seawater, methane emissions have been predicted as negligible. Syntheses of methane emission data from experimental chambers and eddy-covariance flux towers across the United States indicate reduced emissions even in lower salinity settings (as low as 5 ppt), which is important because most coastal wetlands are of lower salinities than half-strength seawater (Windham-Myers et al., 2018a; Arias-Ortiz et al., 2024).

There are many choices for how to manage soils in the Delta, though management opportunities will differ from one area to the next depending on existing conditions. However, all of them require inundating the soil and putting soil back underwater (Windham-Myers et al., 2023). There are three interventions to stop subsidence and restore negative emissions:

(1) Agricultural management for rice
(2) Permanent flooding of impounded wetlands
(3) Tidal connectivity of shallower sites, which will cause the accumulation of peat soils

Both rice agriculture and permanent flooding saturates the soil, resulting in the protection of old dense carbon stocks. Similarly, restoring tidal connectivity saturates the soil and facilitates accumulation of sediment through sedimentation, increasing land elevation. Additionally, marine sulfate in tidally connected sites will likely reduce methane emissions. Current research identified that relative tidal elevation, impoundment status, and salinity were key factors reducing methane emissions in tidally connected sites (Holmquist et al., 2023). All these strategies will be important, particularly when combined with actions that reduce methane emissions to maximize carbon benefits.

Ultimately, the biggest opportunity to apply these strategies is on agricultural land, which covers 90% of the Delta (Whipple et al., 2012). Evaluating the full portfolio of strategies that can be applied will be important to reducing greenhouse gas emissions associated with subsidence.

William Horwath | Biogeochemistry of carbon sequestration and greenhouse gas emissions in inundated peat soils

The carbon content of soils can strongly influence the stability of sequestered carbon. In an experiment examining the impact of different soil carbon concentrations from 2 to 15%, soils with higher concentrations of carbon were more stable, in other words, more resistant to priming, which is the decomposition of older carbon stocks in response to new carbon inputs (Ye and Horwath, 2017).

Soils with only 2% soil carbon had higher methane emissions per gram of carbon of new plant input than soils with 6 to 15% soil carbon. Furthermore, isotope pulse labeling experiments using $^{13}CO_2$ to examine sources of carbon for methane emissions confirmed that methane emissions were consistently due to mineralizing older soil-carbon stocks (priming) (Morris et al., 2017).

Emissions of nitrous oxide and methane, which are greenhouse gases of concern, are sensitive to soil carbon concentrations. In general, both CH_4 and N_2O emissions decrease as the percent of soil carbon increases, though not linearly (Ye et al., 2016). One application of this work is to evaluate whether soil carbon content could be used to model and predict CH_4 and N_2O emissions.

N_2O emissions occur in soils containing between 6% and 11% of organic carbon (Ye and Horwath, 2016). However, at 23% of soil organic carbon, when water levels are brought down, they found a measurable nitrous oxide sink (Ye et al., 2016). Differences in the process rely on managing water levels to saturate the soil enough to maintain high redox levels. Increasing the amount of carbon into the soil could be one strategy to create strong nitrous oxide sinks that could offset methane emissions.

Soil carbon turnover decreases with increasing soil organic carbon (Hartman et al., 2017) because higher organic matter soils have more aliphatic and polysaccharide functional groups (i.e., complex soil carbon compounds). The presence of more complex soil carbon compounds slows down microbial metabolic activity; thereby, increasing the stability and persistence of soil carbon stocks.

Metals also have the potential to coagulate dissolved organic matter to increase soil carbon. Experiments in wetland ecosystems indicated increased vertical accretion rate across the entirety of a subsided area when metal coagulants are applied (Hansen et al., 2018). However, the potential of mercury contamination needs to be considered.

Overall, priming is a risk in soils with lower concentrations of carbon. Soils with higher carbon have lower rates of soil carbon and microbial turnover and have the potential to be nitrous oxide sinks.

Dennis Baldocchi | Lessons Learned from Long-Term Eddy Covariance Flux Measurements of Carbon Dioxide and Methane over Non-Tidal and Tidal Restored Wetlands in the San Francisco Bay-Delta Estuary

Understanding how restored wetlands cycle carbon and methane is important because these biogeochemical processes directly determine whether rewetted peat soils can rebuild elevation and reverse subsidence in the Delta. California has a Mediterranean climate with plenty of water and light and a long growing season. As a result, the Delta has high rates of plant productivity. Wetland restoration, through flooding and saturation of the soil, inhibits oxygen transport to sediments and reduces decomposition rates. High rates of productivity in combination with reduced decomposition allow restored wetlands to accumulate peat, reversing subsidence and building up land elevation over time. However, there is a trade-off. Lack of oxygen creates anaerobic conditions that stimulate metabolic activity of methanogens, which are a type of microorganism that produces methane emissions.

Eddy covariance continuously measures trace gas fluxes from updrafts and downdrafts of wind. Researchers have applied eddy covariance to measure fluxes in the Delta at several different sites that range from tidal to non-tidal systems: West Pond, Mayberry Slough, East End, Gilbert Tract, and Hill Slough. As described during the presentation, previous measurements using the eddy covariance techniques have shown that the carbon sink at Dutch Slough, which sequesters 7,583 pound/acre (850 gram/meter^2) of carbon per year, is in the upper one percentile worldwide when compared to other flux net ecosystem carbon exchange measurements.

Tidal wetlands show substantially lower soil carbon accumulation than expected from eddy covariance measurements, with soil cores capturing only about 13 to 23% of the net carbon fixed annually (Arias-Ortiz et al., 2021). From non-tidal sites, eddy covariance and soil core data are identical. However, in tidal systems, soil core data indicated a much lower amount of carbon sequestered than what was calculated from eddy covariance data. Further experiments will focus on understanding why tidal flows create this discrepancy in observations on Dutch Slough.

One hypothesis of the discrepancy in carbon sequestration rate between eddy covariance and soil core data is that growth in non-tidal systems can be delayed because of the high amounts of senescent material. High productivity in the area stimulates high biomass accumulation and eventually to a considerable amount of dead plant material, that if not managed, can insulate water, keeping water temperatures colder than in tidal systems. Some measurements do indicate a delay in phenology, which shortens the growing period and minimizes the opportunity to take up carbon that could become stored in non-tidal soils. The disagreement between soil core data and eddy covariance measurements also highlights the need to account for lateral flows, which can transport carbon in and out of the system.

The ecological stage of wetland restoration and how water flows can significantly impact fluxes of carbon and methane (Hemes et al., 2018). To build on this point, understanding how wetlands evolve over time is essential for interpreting changes in gas fluxes. Every site is different. As wetlands age and mature, there is variability in the amount of carbon stored and methane emitted (Figure 9). At the Mayberry site, it has been observed that methane fluxes decreased by half since 2012 though it is not clear why. One hypothesis is that the microbial community may be driving these reduced rates in methane production.

Building from site-specific observations, researchers also use modeling approaches to better understand methane dynamics. Simple models based on photosynthesis, temperature, oxygen, and water table have been useful for predicting methane fluxes below about 18.6 nmole $ft^{-2}s^{-1}$ (200 nmole m^{-2} s^{-1}). However, model exercises indicate that there are missing data about what is causing the highest methane fluxes.

These challenges in predicting methane emissions illustrate a broader biogeochemical tension in wetland restoration efforts. Wetland restoration has great potential in the Delta to increase carbon sequestration, but there is a biogeochemical compromise between carbon sequestered and methane emissions that depends on salinity, productivity, and the degree of methane emitted. It is important to monitor over a sustained period to evaluate changes. Research indicates that wetland carbon and methane fluxes are dynamic in space and time and are influenced by the presence or absence of vegetation. For this reason, consistent long-term monitoring is fundamental to understanding how restored wetlands function and how restoration strategies can be improved. Monitoring wetland performance over time is essential because sustained flooding, vegetation development, and soil accretion determine whether restored wetlands are successfully rebuilding peat and slowing or reversing subsidence

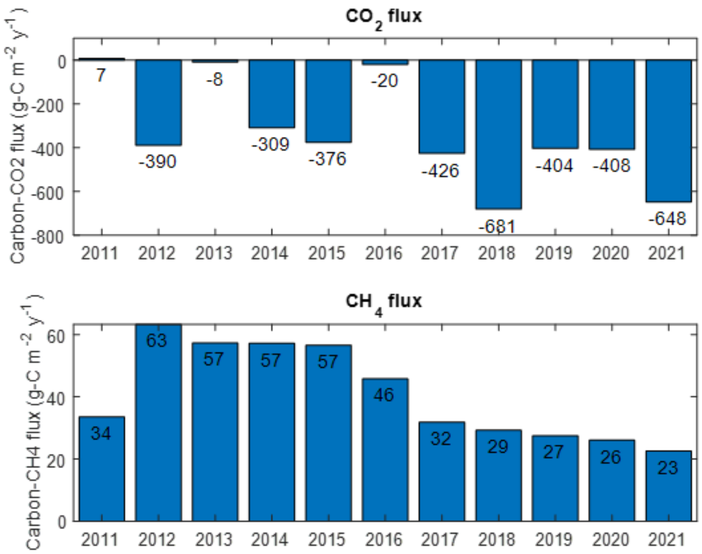


Figure 9. Slide from Dennis Baldocchi's presentation. CO_2 flux interannual variability and a decline in methane production as wetlands age and mature.

Scott Neubauer | Thinking about subsidence in a climate context

Subsidence releases carbon that was previously stored in Delta soils into the atmosphere as CO_2, contributing to greenhouse gas emissions that create a climate impact. Several metrics exist to calculate the influence of management actions on climate:

- Radiative balance
- Radiative forcing
- Lifetime impacts of different ecosystems

Different metrics exist to evaluate the energy budget (radiation balance) of the planet, which directly affects the climate.

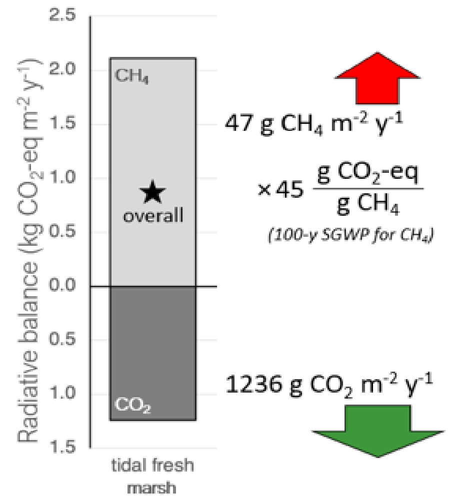
Radiative balance calculates climate over a certain period, usually a century. The calculation ignores ecosystem processes before and after the defined period. To compare the warming due to emission of methane against the cooling due to carbon sequestration, both greenhouse gas fluxes need to be converted into a common currency, such as global warming potential (GWP) or sustained-flux GWP (Neubauer and Megonigal, 2015).

Box 1. Radiative balance information from Scott Neubauer's presentation slides

Use simple metrics to compare different greenhouse gases

- Global warming potential
- Sustained-flux GWP

A positive radiative balance does not necessarily mean a site is contributing to climate change



For methane, its sustained flux GWP is 45, which means that an annual emission of 1 kg of methane has the same warming impact as 45 kg of CO_2. Methane is a much more powerful greenhouse gas. Multiplying methane flux by the sustained-flux GWP places methane impact in terms of CO_2 equivalent units, allowing direct comparison of CO_2 and methane (Box 1). Over a 100-year time period, warming due to methane emissions is greater than cooling due to CO_2 when the net result is positive. However, a positive radiative balance does not necessarily mean that a wetland is contributing to climate change.

For the climate to change, there must be a change in Earth's energy budget. Radiative forcing calculates whether a particular action is contributing to climate change using the radiative balance at two different timepoints. For subsidence, it is possible to calculate radiative forcing due to draining a wetland, which causes the oxidation of organic material and results in CO_2 emissions to the atmosphere. Using values from Windham-Myers et al. (2023) report on subsidence, draining wetlands increases the radiative balance, which increases the radiative forcing, and contributes to climate change. Radiative forcing can also be applied to understanding the effects of other management actions, such as converting the land back to wetlands (Box 2). Various management actions have the effect of potentially reducing radiative balance which means that they are climatically beneficial as well as reversing subsidence.

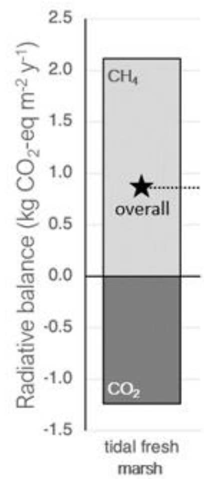
Box 2. Radiative forcing information from Scott Neubauer's presentation slides.

Compare radiative balance at two time points

- Increased radiative balance → warming
- Decreased radiative balance → cooling

Delta example:

- What if this wetland is drained and used for agriculture?
  - Positive radiative forcing = warming effect



Lifetime climatic effects consider the lifetime of a system rather than radiative balance or radiative forcing that consider discrete time points. Evaluating methane and CO_2 emissions for a wetland continuously over 100 years indicates that warming of methane exceeds the cooling effect due to carbon sequestration. However, if the timeframe is extended out, there is a point where the wetland switches from a warming effect to one of lifetime cooling after the wetland is over 200 years old. The reason this occurs is because carbon in soils, assuming no disturbance, is locked away every single year, which continually accelerates cooling whereas the warming effect due to methane only lasts for 50 years. In other words, the warming effect of methane lasts a shorter amount of time (50 years) compared to the cooling due to carbon sequestration. The point when lifetime carbon sequestration is greater than the methane emissions (i.e. the switchover time) depends on the rate of methane emissions relative to carbon sequestration and can differ from one wetland to the other. For example, brackish water will have a lower switchover time than some other wetlands. As long as a wetland remains undisturbed, it will eventually have a lifetime cooling effect on the climate because of carbon sequestration.

Different interventions have the potential to be climatically beneficial in addition to slowing down or reversing subsidence. The basics of wetland biogeochemistry are well understood, but uncertainties remain in the various factors that influence biogeochemistry. For example, it is not clear what determines the magnitude of fluxes in nitrous oxide emissions or fluxes in dissolved inorganic or organic carbon.

In addition, it is important to remember that climate is not the only consideration for managing wetlands and other landscapes. Economics, habitat, and other factors matter as well.

Panel 2 Discussion Summary

Research suggests that rhizosphere carbon root and rhizome production is more likely to be sequestered into soils than carbon from aboveground sources. Plant species may differ in salinity tolerance, but the capacity to store carbon is more related to whether carbon inputs are below-or above-ground. Higher carbon content has been shown to decrease nitrous oxide emissions, potentially through dissimilatory reduction. Managing nitrous oxide emissions may be able to offset methane emissions from inundated soils.

Greenhouse gas emissions from wetland projects can be managed. However, any management action that reduces the radiative balance (e.g., reduce methane emissions), will have a climatic impact with time. The switchover time (the point in time at which a wetland becomes a carbon sink) can change as methane fluxes change. Ultimately, net negative carbon fluxes are not necessary for a wetland project to have beneficial impacts, because a climate benefit occurs if its radiative balance is lower than current values.

Models are essential to understand management implications on ecosystem processes. There are several different types of models and statistical approaches available. However, there is insufficient data to inform model processes and calibrate model outputs, in part because taking measurements is costly and time intensive. Yet determining input data for models requires taking the right measurements to parameterize models, especially because high soil heterogeneity requires hundreds of samples to ensure representativeness of the data gathered.

The lack of good quality data is a major constraint to testing model assumptions. For example, the simple models available that rely on parameters that are easily measured cannot explain the observed fluxes in wetland ecosystems. Developing integrated models that include risk factors such as levee failure will require working on interdisciplinary experiments to understand carbon pools, interactions with nitrogen cycling, and other knowledge gaps such as lateral fluxes, microclimates in soils, and the effect of microbial communities on greenhouse gas fluxes.

Panel 3: Considerations for Inundated Agricultural Practices

Jessica Rudnick | Influences on farmer decision-making

The agricultural sector in the Delta annually generates about $1 billion in revenue and is highly diverse with over 70 crops grown across 415,000 acres (16,7945 hectares). Corn and alfalfa make up the highest proportion of acreage. Wine grapes and tomatoes generate the highest revenue. Most farms are privately held, resulting in many individual landowners across the Delta. Additionally, agriculture supports approximately 13,000 farm jobs and 10,000 processing and manufacturing jobs. Consequently, taking into consideration the whole economy supported by agricultural and other working lands is a key part of the conversation around managing subsided lands.

Economically driven decision making based on return on investment (ROI) and upfront capital costs are high factors influencing the adoption of new technologies or practices (Prokopy et al., 2019; Ranjan et al., 2019). Broadly speaking, access to capital is the most significant factor influencing farm innovation because upfront costs are a key barrier to adoption of new practices. Generally, access to capital increases with farm size such that larger farms and farms that generate higher revenue tend to be more likely to innovate because of their access to greater financial resources with which to experiment. Land ownership can also influence farm innovation, as landowners can operate on longer time horizons, facilitating adoption of innovations that have long term payoffs; whereas farmers leasing land may be restricted to innovation and adoption that will result in ROIs within their land lease term. Overall, a high likelihood and perception that an innovation will be positive to farm revenue will improve the likelihood of adoption.

Learning and access to information can also affect the rate of adoption for new approaches because access to technical knowledge can be a barrier for some growers. Farmers that identify as stewardship-motivated, as well as higher educated farmers, tend to have more awareness of and engagement with incentive programs, extension and technical assistance resources, and practices associated with conservation. For example, growers who are more connected to personnel from the University of California Cooperative Extension, may be more likely to engage with field trials or new practices (Khalsa et al., 2022; Johnson et al., 2023). However, regulatory programs that require mandatory reporting and education have shown to be effective at driving learning among lower-resourced farms and farmers who would otherwise be less likely to engage in conservation programs or adopt new innovations (Wood et al., 2022). For all farms, improving clear communication and access to resources that demonstrate how a new practice will impact crop yields and return on investment can help reduce uncertainty, which is a commonly shared barrier to innovation adoption (Rudnick et al., 2023).

Positive social norms can increase the likelihood of adoption. Peer-to-peer networks and farmer-to-farmer learning experiences, such as through demonstration days, can help growers see the results of adopting a practice. Farmers who have previously adopted conservation practices or who have more experience with vulnerable land, such as farming on actively subsiding areas, are also more likely to engage with new practices and technologies (Prokopy et al., 2019; Ranjan et al., 2019). Improving the spread and accessibility of information about new practices and marketing availability is important to increasing its influence and the adoption of conservation-oriented practices (Prokopy et al., 2019; Ranjan et al., 2019).

In the Delta, farmers reported that economic factors such as impacts to crop yield, crop quality, and farm profitability, were key factors that drive operational changes. Soil health, impacts on public health and safety, stewardship and conservation are highly considered, though secondary concerns. More than 50% of the time, farmers also considered logistical aspects such as regulatory requirements, labor, and complexity. Less than 20% of growers consider incentive programs when evaluating operational changes (Khalsa et al., 2022; Rudnick et al., 2021). The lack of interest in incentives when considering change is consistent with data across California and highlights whether incentives, at least as currently structured, are truly effective drivers of adoption. Variables like the amount of the incentive payment or the costs, in terms of time, technical expertise required, information disclosed in reporting, required to participate in incentive programs may change this trend, but current data suggests that incentives alone do not appear to significantly increase additional (i.e. adoption would not happen otherwise) adoption of conservation practices (Prokopy et al., 2019; Ranjan et al., 2019).

A 2018 survey examining how California growers access information indicated that growers use a variety of different information sources (Khalsa et al., 2022; Rudnick et al., 2021; Johnson et al., 2023). With regards to implementation, it is important to consider how the information is going to be communicated and whether the information is being conveyed by partners that are trusted by private landowners.

On-farm consultants such as certified crop advisors are highly trusted and used by growers. These individuals generally have a wider reach than some of the information sources that are discussed in management and policy context. Natural Resources Conservation Service and resource conservation districts provide technical assistance and demonstration projects, but their reach is not as extensive as private consulting sources. Similarly, familiar sources such as other growers, family members, and field crews are trusted because they have developed one-on-one relationships and are sharing experiences.

There are available incentives to support subsidence management:

- The California Department of Food and Agriculture's Healthy Soils Program directs California's cap-and-trade funds to farmers implementing soil management practices such as cover cropping, tillage, composting, and conservation plantings. This program could support Delta specific soil management practices to reduce subsidence, if there is a quantifiable reduction in GHG emissions.
- The United States Department of Agriculture has several incentive programs:
  - Conservation Reserve Program is not being used in California, but it has the potential to act as a revenue replacement for farms to fallow or retire working farming activities on sensitive habitat lands.
  - The Conservation Stewardship Program and Environmental Quality Incentives Program provides technical and financial assistance to growers for implementing conservation practices on working lands. Getting approval for Delta-specific practices would be one way to leverage a potential new funding source for growers interested in implementing subsidence management practices.
- Carbon market: The payouts on the existing rice protocol approved in the American Carbon Registry aimed at reducing methane are fairly low. Currently, the regulatory market is offering $29 per metric ton and about $2 per metric ton on the voluntary market. The wetland protocol is currently available on the voluntary market. The ability for the carbon market and offsets to motivate growers is difficult, though there is potential for participation in the regulatory market to offset loss in revenues. Offset market participation will need to be made easier and technical assistance for reporting, monitoring, and calculating GHG offsets will need to be available for growers.
- Fish-Friendly Farming (a local program): They provide certifications across the state related to water quality and the incentive is regulatory relief since certification allows growers to meet their compliance requirements for the State Water Resources Control Board.

Michelle Leinfelder-Miles | Considerations for Inundated Agricultural Practices

The University of California Cooperative Extension has existed for over a century in California. Their mission is to connect the people of California with the knowledge and research of the university system through a statewide network of personnel. UCCE is supported through county, state, and federal funding. Programs are developed by working with communities and building trusting relationships for collaboration.

In 2020, the University of California Cooperative Extension released a survey to understand the most important issues in agronomic crop production and the way that the University of California Cooperative Extension could help address those needs (Kanter et al., 2021). Respondents reported that they received information from the University of California Cooperative Extension newsletters, blogs, field days, and speaking with the University of California Cooperative Extension personnel during on-farm consultations. Growers prioritized information on on-farm trial results, costs of production information, and decision support tools. The study also indicated that field crop acreage makes up 45% of the crops grown in San Joaquin County and 70% in Sacramento County. Field crops are economically important crops and are traditional crops that growers can use in crop rotations. These results provided insight into local farming practices and management considerations.

Most of the land in the Delta is under private ownership. Thus, private landowners make up a large footprint in the region. The challenge is that most desirable crops cannot grow under the flooded conditions that would reduce subsidence. Rice is the exception because its cellular structure allows gas diffusion throughout the plant, meaning that rice cultivation is uniquely suited to addressing subsidence while generating profit.

The Sacramento Valley is the predominant rice growing area in the state, but Delta acreage is increasing. In 2022, rice was grown on approximately 10,000 acres in the Delta compared to approximately 3,000 acres a decade before. Acreage is expected to expand in the future. Delta growers have engaged in research to advance the rice industry by exploring cold tolerant rice varieties. This is an example of research that can provide growers with actionable information in the short-term that also supports long-term priorities for the region.

Inundating the Delta landscape supports public interests like mitigating subsidence, which threatens levee stability and water quality. Private landowners understand the importance of these goals, but must also be concerned with crop profitability and markets. Economics is a critical aspect of on-farm decision-making. Another study (Leinfelder-Miles et al., 2022), in collaboration with Delta growers, examined the cost of production for Delta rice, considering the cost of converting land for rice cultivation. The study benefits growers who are not currently growing rice but are interested in learning more, banks and lending agencies, and state and federal agencies to inform their cost sharing and incentive programs.

There are several science gaps that still remain:

- Alternate wetting and drying (AWD) has been discussed as a way to reduce methane emissions, but it has not been proven in the Delta where soils differ from original studies that related AWD to reduced methane emissions (which took place in Arkansas).
- Walking wetlands, which are temporary short-term wetlands, may strike a balance between minimizing subsidence and allowing crop rotation. It may allow for receiving emissions reduction benefits while regenerating land to increase crop yields.
- Programs that support dewatering of subsided lands, such as drought programs, would likely have a negative impact on subsidence. The University of California Cooperative Extension has deployed eddy covariance data to currently evaluate this.

In conclusion:

- Research needs to be supported by making sure that strategic planning documents include land-based priorities. Project evaluations need to include appropriate personnel so that proposals are evaluated fairly by personnel that understand the land-based priorities. Because subsidence is fundamentally a land-elevation and land-management issue, integrating land-based priorities ensures that projects are sited where they can most effectively slow peat oxidation, rebuild elevation, and reduce levee risk.
- Financial programs that enable cost-share could increase adoption of rice because land conversion for rice cultivation has high upfront costs. The 2022 Cost of Production Study for rice indicates that supporting private growers in land conversion is more cost-effective than relying on meeting stewardship goals on public lands (Leinfelder-Miles et al., 2022). Expanding rice cultivation is directly relevant to subsidence because rice keeps soils saturated, reduces microbial oxidation of peat, and helps stabilize elevations; therefore, cost-share programs can accelerate adoption of practices that measurably slow or halt subsidence on privately owned lands.

- Long-term requirements for carbon sequestration are barriers to practice adoption on private lands and especially on leased land, which accounts for 50% of farm acreage in the region.

Jerred Dixon | Considerations for Inundated Agricultural Practices

Staten Island was purchased by The Nature Conservancy in 2001 to create a conservation- and agriculture-friendly island. Research studies that focus on migratory birds, subsidence reversal, and carbon sequestration have been completed on Staten Island for over 20 years, resulting in a living laboratory that supports farming and habitat for migratory birds.

The Nature Conservancy is interested in science that addresses walking wetlands, alternative wetting and drying, carbon sequestration and rice, which are all topics that add to their understanding of current activities. For rice, land leveling and building the necessary water structures are costly and one of the largest hurdles for increasing adoption of rice.

Staten Island is also recirculating water in wetlands and rice fields to minimize impacts on water quality. They are in the process of registering this project through Fish Friendly Farming.

The public sector adoption of rice is supported through grants, but those funds are largely inaccessible to private landowners. Private landowners manage about 400,000 acres of agricultural land in the Delta. Enabling access to funding for the private sector to convert agriculture lands into wetlands and rice would be an effective strategy to increase beneficial land uses. Developing ways to provide funding to private landowners who have large land holdings would solve a major disconnect. Outreach to landowners is necessary because as other farmers see profitability in these actions, they will be more likely to adopt them.

Benjamin Leacox | Considerations for Inundated Agricultural Practices

Farmers care greatly about sustainability, but there are two aspects of this: (1) making sure that land can be farmed in the future and (2) financial stability. Farmers can visibly see losses of farmland on the margins because land is becoming difficult to farm due to subsidence. Some of this land could be converted into wetlands to help reverse subsidence, but the incentives for conversion currently are not sufficient. Farmers are open to incentives and alternative land uses, but incentive programs need to work for farmers. For example, 40-year programs to participate in the carbon market are not feasible because many farms operate on a year-to-year basis and are unwilling to tie ground up for decades for little financial benefit.

Financial stability is the main concern because income is needed to maintain operations. Without income, farming operations stop. So, financial decisions and ensuring returns on investments are key priorities. Zuckerman Farms has converted land to rice on land that they own at $800 to 1000 per acre because they are confident about their return on investment. A key question is how to rotate high profit crops, such as potatoes, with rice, which is not as profitable, so that operations can be maintained. Prices for rice vary from year-to-year, requiring rotation with other crops to maintain profitability. Currently, rice is being used as a replacement for corn because corn contributes to subsidence.

At least 50% of the acres operated by Zuckerman Farms is leased typically for 5-year terms. This makes it more complicated to implement conservation practices because 5 years may not be long enough to guarantee a return on investment. Additionally, leasers are hesitant to sign 5-year contracts.

Incentives can work when they minimize the risks to farmers for converting land into rice. If the costs for conversion could be eliminated or subsidized, it would increase the conversion process for rice in the Delta. Incentives have typically been onerous or have financial caps or terms that are not adequate for the level of work being asked. This is why incentives have not been as influential in farmer decision-making. However, well-designed incentives can motivate adoption. The Delta Drought Response Pilot Program is an example of a successful program that was implemented correctly. When programs are designed well, they can help growers make land management decisions that are helpful for everyone.

Panel 3 Discussion Summary

Most of the Delta is owned by private landowners. Involvement of the private sector is crucial for landscape-scale subsidence management because the volume of subsidence reversal required is not achievable on public lands alone. Thus, efforts to consider how private landowners can contribute to landscape goals is essential. Private landowners are interested in converting lands to land use types that can mitigate subsidence, particularly land that is already too wet for farming. In some cases, this can be integrated into crop rotation, which is an important technique in the Delta that involves planting different crops in the same area across growing seasons for a variety of reasons including improving soil fertility and managing pests and diseases. However, high upfront costs, regulatory constraints, and lack of funding opportunities hinder farmer and landowner conversion of subsided lands.

One of the challenges is the permitting process for wetlands, which is both time- and cost-intensive. Farmers expressed frustration that they must wait on permitting processes and the associated costs that prevent them from accomplishing desired land conversions. A wetland can cost over $10,000 per acre for construction due to regulations, which farmers feel “slows down” what they could accomplish. Public agencies likewise feel limited by regulations and the costs to create wetland projects. These concerns from both the private and public sector highlight the importance of understanding how to structure and implement incentives.

Currently, growers pay to convert land use from agriculture into rice or wetland development out of pocket much of the time, requiring significant upfront investment. As a result, land conversion for subsidence reversal is only possible for larger farms that have access to capital despite a general interest from landowners. Ideally, the agricultural sector could be compensated for implementing management practices and land uses that provide societal landscape benefits such as reducing carbon emissions and minimizing subsidence.

The voluntary carbon market has emerged as a potential incentive to reward converting land for rice cultivation or wetlands. However, it is not clear to private landowners that carbon credits are a viable source of profit due to the low price for carbon in the voluntary market compared to the compliance market. Until the California Air Resources Board approves a wetland carbon market protocol, participants are limited to participating in the voluntary market. Monitoring, reporting, and verification costs to register credits are also time- and cost-intensive to complete. Furthermore, available protocols that award carbon credits in exchange for a 40-year commitment to growing rice, given that a typical contract is 5 years, is too small an incentive for private landowners. Increases in voluntary carbon market prices or the option to participate in the compliance market may change engagement in the carbon market. Ultimately, incentive structure is crucial for building participation. Incentives must have cost-effective options that account for operating costs, taxes, and levee repair costs that private landowners take into consideration when making day-to-day decisions. Additionally, the trade-offs among different management actions related to reducing subsidence are not clear, preventing the development of clear metrics or guidelines for incentive programs.

Rice is one of the few crops that can grow in saturated soil conditions and that has a stable market sufficient to make profit. There are also practical challenges for growing rice, such as leveling land, and the routine maintenance of rice fields is time intensive. The associated costs are often paid for out of pocket by farmers. However, for farms that have introduced rice into their crop rotation, they have observed higher yields in high profit crops like potatoes and turfgrass. While there is interest among farmers to increase the acreage of rice grown, the high upfront costs remain a major barrier in converting lands for rice cultivation. Furthermore, flooded conditions in rice cultivation promote methane emissions. Ongoing research in the Healthy Soils Program is evaluating the tradeoffs between methane emissions and CO_2 reduction. However, there are no applications for this right now.

Alternate wetting and drying (AWD) for rice agriculture is intended to reduce methane emissions by intermittently draining flooded rice fields. The theory behind AWD is that drying out the soil will minimize the populations of Archaea, a group of microorganisms that thrive only in low-oxygen conditions and generate methane, thereby reducing the capacity of the soil to produce methane when it is later flooded. The goal is to minimize populations to a low enough level that even after wetting the soil, there will be a 2-to-4-week period of lower emissions of methane because there is a reduced amount of Archaea and it takes time for that population to increase. However, the theory of AWD relies on one study from Arkansas with only two field studies and chamber measurements, which needs to be verified in the Delta. The timing of this process in the Delta needs to be examined further, especially because it might not be possible to fully dry out the soil. Furthermore, farmers generally do not want to truly drain the soil when growing rice because adequate yields require flooded soils. This practice effectively negates the benefits of AWD, but AWD should be tested in the Delta to better understand what the benefits are since agronomic practices can be unique to the region. The Arkansas investigation clearly states that experiments are needed to test how to apply AWD without risking rice yields. There are also data from a UC Davis AWD study (see LaHue et al., 2016) that suggests that there are potential ways to manage this, particularly if the timeframe is kept in mind.

Walking wetlands as a means of rotating the land through different land uses has been tried with mixed results. Walking wetlands appear to be beneficial for birds and re-building soil, but it is not clear what the impact of walking wetlands is on profits, nor on longer term ecological processes (such as the release of heavy metals and toxic compounds), and the method has yet to be tested in a crop rotation with rice. The theory of walking wetlands is to develop them as part of a crop rotation to receive the benefits, especially because they are compatible with current farm infrastructure and therefore could be economically beneficial. Additionally, they are not subject to the same level of regulations as is typical of permanent wetland projects. However, further refinement is needed to determine the benefits.

Farmers generally operate on a 5-year planning horizon because land might be leased or because contract lengths are traditionally less than 5 years. This timeframe forms the backdrop for day-to-day and year-to-year decisions, complicating efforts to implement long-term planning for subsidence management. Immediate concerns such as ensuring enough revenue to support levee repairs, which can average $2 million per mile, are important factors that significantly impact crop choices and land uses. However, farmers expressed strong interest in actionable information and openness to implement practices that generate long-term benefits. A major barrier is the lack of conduits to communicate actionable information to farmers and a lack of studies on approaches to manage subsidence within a profitable crop rotation framework. Furthermore, data on how farmers learn from each other and transfer knowledge are lacking, highlighting a major social science gap in ways to communicate effectively within the Delta agricultural community. Developing relationships and demonstrations focused on actionable information is needed to promote subsidence management on an effective spatial scale.

Panel 4: Science Needs to Inform Landscape Implications of Peat Soil Inundation

Many interconnected and significant science issues relate to subsidence. They include water quality, ecosystem health, flood risk, and greenhouse gas emissions. One aspect of subsidence directly relevant to California state goals is the associated greenhouse gas emissions. California has a goal of reducing emissions and moving toward carbon neutrality. AB 1757 is intended to address carbon issues for the State by incorporating emissions and sequestration from the landscape into state projections for carbon neutrality. The policy applies to “natural and working lands”, which are defined as: forests, shrublands, grasslands, croplands, developed lands, wetlands, and sparsely vegetated lands. California develops a scoping plan every five years that calculates emission projections and includes approaches to reduce net emissions. The most recent scoping plan was released in 2022 and covers emissions through 2045.

Delta wetlands are the only wetlands incorporated into State's projections because of the size of the Delta and availability of data and modeling. The current target set by the State is to restore 50,000 acres of wetland by 2045, which includes tidal wetland restoration, managed wetlands, and rice cultivation.

A Natural Working Lands Expert Advisory Committee of 15 members with expertise across the seven land types provides input to the California Air Resources Board and the California Natural Resources Agency about scoping plan targets. It also recommends improvements to the approaches used for modeling projected emissions. The wetlands advisory group recommended increasing the original wetland restoration targets to 50,000 acres of managed wetlands and rice cultivation and 32,500 acres of tidal wetland restoration.

Karen Buhr | Science Needs in the Delta

The Sacramento-San Joaquin Delta Conservancy is a state agency that focuses on environmental protection and economic well-being of the Delta. The agency funds projects and forms state-local partnerships to meet local challenges, such as subsidence, and to support work that is happening locally. The main role of the agency is to provide funding and state and local resources to advance projects that address the following objectives:

- Climate adaptation and restoration
- Supporting farmers and ranchers on working lands
- Drought programs such as the Delta Drought Response Pilot Program
- Community programs to increase public access to the Delta and to provide community centers
- Education and enrichment for various audiences
- Nature-based restoration efforts

One of the major efforts of the Conservancy has been the development of carbon market protocols for the region. The Conservancy is interested in incentivizing and increasing the scale of the carbon market to increase implementation of wetland restoration and/or rice cultivation, especially on lands that are too wet to farm. Three projects in the Delta currently are using the 2017 carbon market protocol to which the Delta Conservancy provided technical and financial support: Sherman and Twitchell Islands, Staten Island, and Webb Tract (Deverel et al., 2017).

The Conservancy has $36,000,000 in their Wetland Restoration Funding to fund nature-based solutions. Currently, this program has awarded funds for the Webb Tract Wetland and Rice Mosaic. Proposals on Staten Island will be evaluated as well. The funding is a significant opportunity to implement restoration at a larger scale.

Science needs include:

- Guiding project implementation. How can current models be refined? How do systems actually work ecologically?
- Quantifying carbon savings. How can the Conservancy better understand what is happening on the ground across different regions, the degree of subsidence, and management actions?
- Economic data and modeling for farmers. Switching crop types is a huge investment. Therefore, what data are needed and how can that information be provided to make timely decisions?

Funding is a major constraint to implementing wetland restoration projects. Educating the public and legislature about the projects and their benefits can help minimize financial constraints impeding completion of projects in the Delta.

Steve Deverel | Landscape Scale Implications

Eddy covariance flux towers, which continuously measure gas exchange between the land surface (soil and vegetation) and the atmosphere, have been critical for quantifying carbon fluxes, including estimating the net greenhouse gas emissions reductions benefits for the carbon market. Cultivated agricultural lands generate baseline emissions. Converting land to wetlands sequesters carbon, but releases methane. The balance between carbon sequestration and methane emissions of a wetland in comparison to the baseline agricultural emissions determines the net greenhouse gas reduction benefit. These greenhouse-gas measurements are also central to subsidence research because they show whether restored wetlands are accumulating enough carbon in the soil to rebuild peat and raise land elevation over time. However, there are several concerns with the way the estimated net greenhouse gas benefit is calculated.

One concern is that the atmospheric warming impact of methane emissions (methane is a stronger greenhouse gas and shorter lived in the atmosphere than carbon dioxide) is typically calculated using a global warming potential of 28. This is the standard for the carbon market, but it is lower than what some research indicates. Secondly, participation in the voluntary carbon market requires a 40-year contract and the compliance market requires a 100-year contract (Deverel et al., 2017). The purpose of these long contracts is to ensure that wetlands are undisturbed long enough to reach the switchover point when the wetland becomes a carbon sink. However, long-term contract lengths can be difficult for potential participants, particularly farmers, who must deal with the reality of generating an income from these lands.

Twitchell and Sherman Islands were the first projects in the Delta and the world to verify wetland carbon offsets, a total of 52,106 tons of CO_2e, under the American Carbon Registry protocol in 2020 (Deverel et al., 2017). Carbon prices are expected to increase over time, which could make carbon markets a potential tool to incentivize new land management practices.

Landscape scenario analysis for islands that considers alternative patterns of crops such as corn, potatoes, rice, pasture, and alfalfa as well as wetlands permits assessments of subsidence mitigation and GHG emissions and removals. Analysis of alternative scenarios identify impacts of using the same land in different ways. For scenarios of six different land mosaics for Staten Island, subsidence reversal and greenhouse gas emissions reductions were compared as well as estimating revenue compared with the baseline. Changing land uses and allocating more land to wetlands and rice where subsidence and baseline carbon dioxide emissions are the greatest, can both mitigate elevation loss and, in the case of wetlands, reverse the effects of subsidence (Deverel et al., 2016b, Deverel et al., 2020). Analysis of the economics for the different mosaics indicate that they can generate income consistent with or exceeding the baseline in which most the island was planted to corn (Deverel et al., 2017).

Research needs for adaptation to the carbon market and land management include:

- Improved understanding of GHG emissions and sequestration for alternative landscape scenarios.
- Improved understanding of the impact of different management practices, e.g., crop rotation, soil wetting and drying etc., on GHG emissions and sequestration.
- Quantification of co-benefits of land use changes to food webs and levee stability.

Modeling suggests that establishing wetlands near the periphery of islands decreases the risk of levee failure by decreasing critical hydraulic gradients that can erode levee foundation material. On Bacon Island, a groundwater flow model was integrated with models that predicted subsidence and organic soil accumulation to evaluate seepage forces on levees from 2018 to 2070. The model simulations compared a business-as-usual scenario to a scenario where rice was grown in the central part of Bacon Island and wetlands were established at the periphery of the island. Model results indicated that the scenario with wetlands and rice significantly reduced the relative probability of levee failure and seepage forces compared to the business-as-usual scenario. The business-as-usual scenario resulted in critical exit gradient exceedances in 1,542 yards (1,410 meters) of levee in 2070. The rice/wetland scenario resulted in zero. The benefit of this approach is that it identifies areas that have a higher risk potential of seepage threats to levees.

Jay Ziegler | Managing Subsidence in the Sacramento-San Joaquin Delta

There are ~600,000 residents in ~738,000 acres of reclaimed environment in the Delta. Polling indicates that the public is very concerned with aging infrastructure such as roads and levees, affordability, public safety, environmental decline, and climate change. Levees are incredibly resilient, but people are understandably very concerned about the levee system because they are not natural systems. The coequal goals of the Delta Plan are in conflict, which creates very complex challenges. As the State Water Resources Control Board considers subsidence and its impact on carbon budgets, it’s important to consider people.

There are significant regional differences across the Delta that pose different challenges and opportunities when it comes to addressing climate risk reduction, carbon credits, and other problems. Different regions have different issues. For example, in the northern Delta, opportunities for habitat restoration are in the intertidal range and maintaining flow for the Yolo Bypass are key priorities. However, in the eastern Delta, floodplain restoration is a bigger concern and widening the separation of the levees along stream channels so that excess river flow can be absorbed is a major priority. The State Water Resources Control Board needs to align efforts about enhancing carbon sequestration along with the values of people across the Delta landscape and where there are opportunities, such as Suisun Marsh and Cache Slough, for restoration.

The Delta community must be an active part of the process to ensure that implementation is related to practical concerns on the ground to be effective. Choices in land use should be shaped by the local needs, priorities, and ecosystem opportunities. Ideally, habitat, flood protection, and groundwater programs would be aligned to sub-regional carbon benefits that in turn align with landscape-scale strategies.

The State Water Resources Control Board does not have good data on how much water is being used in the Delta. Careful tracking of water use is needed because California has the most variable annual precipitation in the United States. OpenET aims to improve water data availability. There are ~1,300 water rights holders in the Delta and ~3,000 points of diversion, 75% of which are reporting now on the OpenET system. OpenET allows validation of where, when, and how much water is used. This system is setting the standard for water budget accounting because OpenET allows us to know consumptive use in the Delta exactly. The data from OpenET can then be used to exercise water rights in a way that protects water quality.

The error range for OpenET calculations on consumptive use for land-based applications of water is within 10%, which provides an accurate estimate of the Delta water budget. However, for open water such as wetlands, the error range is about 25%, indicating that OpenET methodology remains difficult to apply accurately for wetland restoration or open water with tule vegetation. It is recommended that OpenET should not be used for those cases. Overall, OpenET allows us to have grounded, quantitative, conversations about water use that uses one database. It is important to have science-based discussions about the multiple values of water when thinking about carbon and land strategies.

Funding has been central to conversations in this workshop. In comparing fiscal year 2021 to fiscal year 2024, there has been a ~30% reduction in funding for environmental purposes. Improvements to funding for climate and natural resource investment are necessary and the scientific community needs to be an active voice that expresses the importance of investments in the future.

Incentives to address climate vulnerability need to be rebalanced and ordered to improve participation. Farmers are not very confident in the carbon market though there is interest in climate smart agricultural practices. If the risk of investment for converting land to rice was removed from the farmer, that could encourage adoption of that practice. In general, a portfolio of incentives could be re-structured to align tax benefits with first adopters that are really trying to address climate challenges through smarter land use changes. The Farm Bill could be re-structured to minimize the risks to farmers who apply climate-smart practices. Sustainable

Agricultural Lands Conservation program (SALC) could be modernized to address climate resilience rather than just for agricultural protection. Currently, farmers do not see a real incentive to change farming practices to align with climate smart strategies. It is critical to evaluate the current portfolio of incentives and the proportion of public and private incentives to examine whether they are meeting people where they are in order to ensure that there are beneficial changes in the landscape. There is a need for open, transparent, and strong community engagement to achieve these goals.

Panel 4 Discussion Summary

Subsidence is related to many issues such as the Delta carbon budget, contaminants, and water quality. Severe subsidence in some areas intertwines subsidence management with levee maintenance as well, because seepage that occurs in deeply subsided areas can erode levee foundations. Thus, subsidence could be considered an infrastructure issue that increases with climate and generates expensive levee upgrades.

One key concern is the potential for wetlands and rice fields to create conditions that could lead to the formation of methylmercury. Studies from Twitchell Island show that methylmercury in fish exceeds the State's threshold for concern, which indicates that it is not prudent to put fish in rice paddies (Deverel et al., 2007; Twitchell Rice Project Report 2008-2009; Heim et al., 2009; Stumpner et al., 2015). Even if the concentration is low, it can accumulate in the food chain. However, there are water management alternatives to reduce methylmercury contamination like recirculating water so that it does not end up in more than one location. There is a seasonality to methylmercury exports as well. Mercury exports are highest in the winter, but there are also higher flows at that time so there is more dilution (see Yolo Bypass studies: Windham-Myers et al., 2010; Lee and Manning, 2020).

OpenET enables, for the first time, an accurate accounting of consumptive use in the Delta. For subsidence, the data in OpenET can be used to exercise water rights in a way that protects water quality and provides a way to understand the variation in water use across the entire Delta. Opportunities to manage subsidence vary by area , and new tools and resources will be essential to developing strategies and governance structures that align with community objectives and local opportunities. Focused dialogue, especially with farmers and private landowners, on land use and potential approaches for different scales is needed to understand what types of governance structures are needed. Although dialogue and collaboration with farmers has improved significantly over time, communication with the legislature could be improved.

Farmers have different preferences for receiving information. Some data are available to help guide strategies of how to maximize effective communication methods. Staten Island effectively serves as a model and source for preliminary information. Costs of production study like those produced by the UC Cooperative Extension (for rice) are also important for providing numbers and the assumptions to support calculations (e.g., Leinfelder-Miles et al., 2022). The newsletters, blogs, and annual grower meetings sponsored by the UC Cooperative Extension are the main options growers have to a guidebook for various practices and their potential benefits. Other groups are also working to disseminate information, including bringing growers to look at recirculation pumps. Farmers expressed concerns that they are not heard. Efforts to include farmers in land use discussions in a way that is sensitive to their interests must take place to work with them to implement solutions.

Several resources and tools are available to help implement different management practices. However, farmers expressed that currently available incentives are inadequate to motivate larger scale land conversions particularly for land that could be used to farm profitable crops. Experiments that generate actionable information and tools are necessary, as are more effective ways to communicate with farmers and private landowners. New technologies that enable real-time monitoring may be leveraged to help close the gap between the development of data and the application of that data to improve management practices that reduce subsidence and methane emissions.

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