Delta Wetland Futures:

Blue Carbon & Elevation Change

SFEI | AQUATIC SCIENCE CENTER

Delta Wetland Futures: Blue Carbon & Elevation Change

PRIMARY AUTHORS
Lydia Vaughn[1]
Stephanie Panlasigui[1]
Steven Deverel[2]
Judith Drexler[3]
Marc Olds[2]
Jose Diaz[2]
Kendall Harris[1]
James Morris[4]
Letitia Grenier[1]
April Robinson[1]
Donna Ball[1]

DESIGN AND LAYOUT
Katie McKnight[1]
Ruth Askevold[1]

DECEMBER 2022

PREPARED BY
San Francisco Estuary Institute-Aquatic Science Center

AFFILIATIONS
[1]San Francisco Estuary Institute-Aquatic Science Center
[2]Hydrofocus, Inc.
[3]California Water Science Center, U.S. Geological Survey
[4]University of South Carolina

FUNDED BY
California Department of Fish and Wildlife and through the Proposition 1 Delta Water Quality and Ecosystem Restoration Grant Program

SFEI PUBLICATION #1105

SAN FRANCISCO ESTUARY INSTITUTE & THE AQUATIC SCIENCE CENTER

ACKNOWLEDGMENTS

Support for this work was generously provided by the California Department of Fish and Wildlife through the Proposition 1 Delta Water Quality and Ecosystem Restoration Grant Program. We are grateful to our expert advisors for providing guidance on project design and interpretation: Ariane Arias-Ortiz, Dennis Baldocchi, Kevin Buffington, Dylan Chapple, Steve Crooks, Campbell Ingram, Patty Oikawa, Lisa Schile-Beers, and David Schoellhamer. We also thank Daphne Szutu for assistance with data compilation.

SUGGESTED CITATION

SFEI. 2022. *Delta Wetland Futures: Blue Carbon and Elevation Change.* Publication #1105, San Francisco Estuary Institute, Richmond, CA.

Version 1.0 (December 2022)

COVER CREDITS

Cover photo by Shira Bezalel (SFEI)

CONTENTS

BLUE CARBON IN THE DELTA vi

PAST AND PRESENT PEAT CARBON STOCKS 2

METHODS 2

RESULTS 3

FUTURE RESTORATION SCENARIOS 4

FIVE FUTURE SCENARIOS 4

SCENARIO ANALYSIS 6

FUTURE MODELING RESULTS 8

POTENTIAL TO MITIGATE SUBSIDENCE AND BUILD ELEVATIONS 8

POTENTIAL TO REDUCE OR REVERSE FUTURE PEAT CARBON LOSSES 9

HIGH REFERENCE SCENARIO GHG EMISSIONS 10

LARGE REDUCTIONS IN GHG EMISSIONS IN WETLAND RESTORATION SCENARIOS 11

MULTIPLE BENEFITS FOR ECOSYSTEMS AND PEOPLE 12

CONCLUSIONS 14

RESOURCES & RELATED EFFORTS 15

REFERENCES 16

BLUE CARBON IN THE DELTA

Carbon-rich peat deposits lie beneath the farmlands and wetlands of the Sacramento-San Joaquin Delta. Historically up to 60 ft thick, this peat represents roughly 6,700 years of carbon dioxide uptake and carbon sequestration by the Delta's historical wetlands (Drexler et al. 2009a). Once a blue carbon ecosystem—a tidal freshwater wetland covering ~420,000 acres—the Delta's historical tidal wetlands accumulated deep carbon stocks as sea levels gradually rose after the last ice age. Ninety-eight percent of those wetlands have since been drained, leading to extensive subsidence, peat carbon losses, and high ongoing greenhouse gas (GHG) emissions. Over the past 200 years, a layer of peat up to ~30 ft thick in some places has disappeared from the Delta (Drexler et al. 2009b; Deverel and Leighton 2010), reversing millennia of climate protection, stressing the Delta's levees, and threatening California's water supply (Deverel et al. 2016a).

Ongoing land-surface subsidence and sea level rise present profound challenges for the future Delta. Accordingly, the science, management, and policy arenas have seen an increasing focus on the potential for alternate land uses in the Delta to stop or reverse subsidence, sequester carbon and reduce GHG emissions, and restore natural processes and ecosystems to support imperiled species.

A note about units: A mix of metric and imperial units has been used in this report in order to align with standard practices of the management and science communities. Measures of area, length, and volume are expressed in units of acres, feet and cubic feet—units commonly used by resource managers. Carbon and GHG emissions are expressed as metric tons (MT) or million metric tons (MMT), the standard units used in US and international GHG inventories. Metric units are also used for the density of carbon in peat, in order to facilitate comparisons with other published values. In some cases both metric and imperial units are provided.

Photo by Shira Bezalel, SFEI

This report explores opportunities to protect and restore the Delta's blue carbon stocks through large-scale land-use changes. Establishing wetlands in drained and subsiding sites can halt carbon losses and build new peat, reducing GHG emissions and rebuilding elevations while providing other benefits for ecosystems and people (Miller et al. 2008; Deverel et al. 2014; Deverel et al. 2016b; Hemes et al. 2019). Tidal wetlands, nontidal "subsidence reversal" wetlands, and rice are three wetland land uses that can each play a role in a sustainable future Delta. To envision a future Delta that supports the climate, native ecosystems, and the region's agricultural heritage, large-scale scenario analysis can be used to set meaningful restoration targets, define priorities, and identify where management actions offer multiple benefits or entail tradeoffs between objectives.

Figure 1. Location map of the Sacramento-San Joaquin River Delta, the area analyzed for this project.

This study evaluated the effects of Delta land use scenarios on peat carbon stocks, GHG emissions, and other ecosystem functions. We asked the following questions:

Q1: What mass of blue carbon was stored during the Holocene and lost since the 19th century?

Q2: What is the potential upper bound for GHG benefits and peat carbon accumulation through wetland restoration and rice cultivation in the Delta?

Q3: What magnitude of GHG emissions reductions and peat carbon storage could existing Delta wetland restoration and rice farming targets achieve?

Q4: How can the configuration of wetland restoration and rice cultivation be optimized for GHG mitigation and other restoration goals?

Photo by Shira Bezalel, SFEI

What is blue carbon?

Blue carbon is carbon stored by coastal and marine ecosystems. Although the Delta is now primarily agriculture, it was once the largest freshwater estuarine wetland on the west coast of North America.

PAST AND PRESENT CARBON STOCKS

Q1: *What mass of blue carbon was stored during the Holocene and lost since the 19th century?*

METHODS

▶ **Peat thickness mapping**:
To map peat thickness across the historical and modern Delta, we combined maps of modern peat thickness and surface elevations (Deverel and Leighton 2010; DWR and USGS 2019) with a reconstructed digital elevation model for the early 1800s (Robinson et al. 2014; RMA 2015). We assumed that within the historical extent of the Delta's tidal wetlands, elevation losses since the early 1800 were due primarily to compaction and microbial oxidation of peat.

▶ **Core data synthesis**:
We synthesized carbon data from 23 peat cores from farmed islands and remnant wetlands in the Delta (Drexler et al. 2009a,b; Callaway et al. 2012; Craig et al. 2017; Anthony and Silver 2020; Drexler et al. 2021). Cores spanned a range of landscape positions and varied in depth from 50 cm (1.6 ft) to 9 m (30 ft) below the soil surface. We looked at patterns in carbon and peat density to identify carbon density values for different land uses and depths.

▶ **Mapping peat carbon:**
We applied carbon density values to mapped peat volumes to estimate the mass of peat stored in the historical (ca. 1800) and modern (2017) Delta.

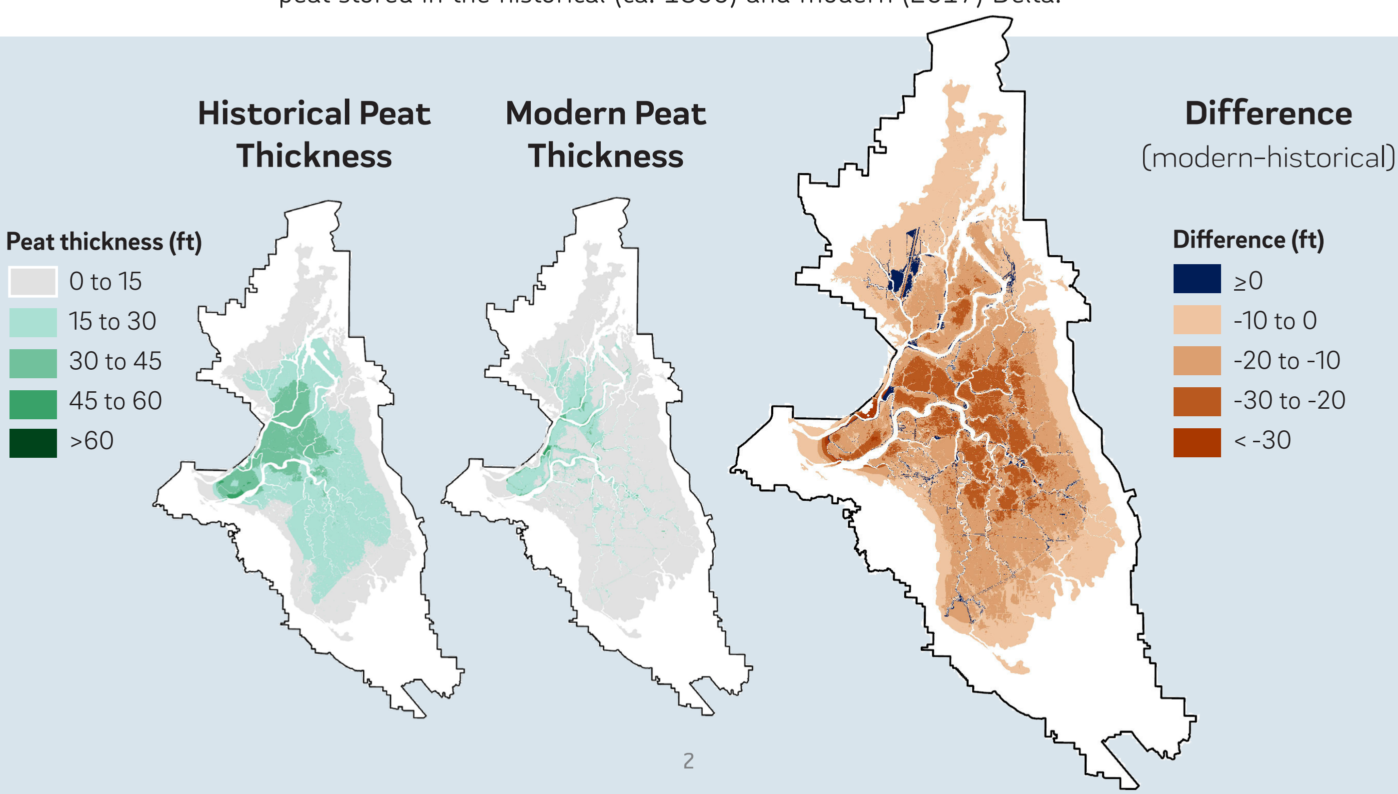


Figure 2. Mapped changes over time in peat thickness in the Sacramento-San Joaquin Delta. The historical map reflects modeled peat conditions in the early 1800s, and the modern map depicts estimated peat thickness in 2017. Mapped differences in peat thickness show changes due to oxidation and compaction, where positive values indicate peat accumulation and negative values indicate peat volume losses.

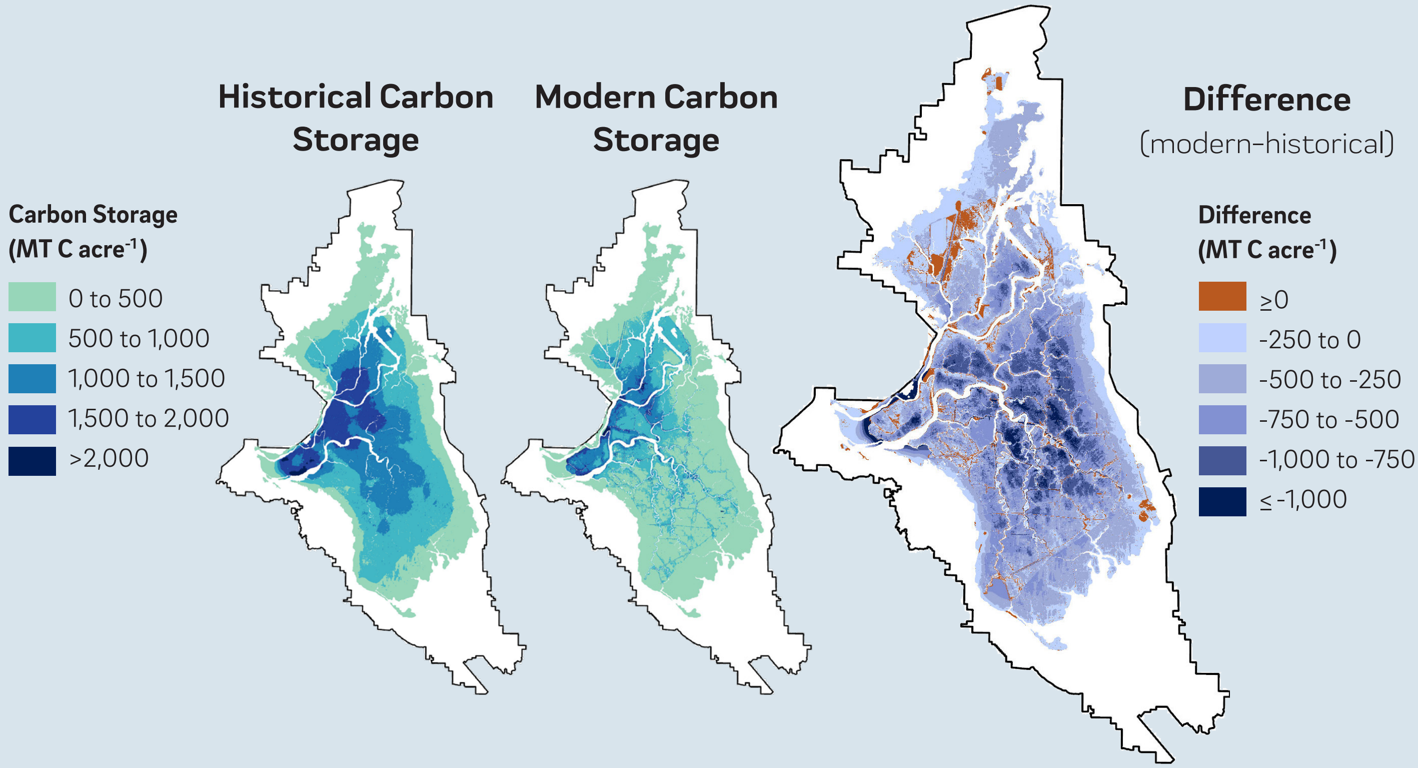


Figure 3. Mapped changes over time in peat carbon storage in the Sacramento-San Joaquin Delta. Compaction and microbial oxidation have altered the carbon density of peat, so maps reflect both peat thickness and spatial variations in estimated carbon density. The historical and modern map depict modeled peat carbon stocks in the early 1800s and 2017 respectively. Mapped differences show changes in carbon stocks due to oxidation and compaction, where positive values indicate a net increase in carbon storage between historical and modern conditions.

RESULTS

- In the early 1800s, the Delta stored an estimated 280 million metric tons of carbon (MMT C) in its 180 billion cubic feet of peat. (This volume is equal to ~2,000 olympic-size swimming pools.)
- Over the past two centuries, approximately half this carbon has been lost to oxidation. The Delta now stores an estimated 99 billion cubic feet of peat and 140 MMT C.
- This loss of ~140 MMT C is equivalent to clear-cutting over three and a half million acres of forest or burning half a trillion pounds of coal.
- By using a reconstructed historical DEM to map early-1800s peat, we were able to account for areas where there is no remaining peat. This led us to a value for historical peat carbon storage that is 40-90% greater than previous estimates based on subsidence rates and accommodation space within existing peatlands (Mount and Twiss 2005; Deverel and Leighton 2010; Drexler et al. 2019).
- Surface soils on Delta farmed islands are over twice as carbon-dense (97 ± 37 kg C m^{-3}) as deeper peat layers (46 ± 4.2 kg C m^{-3}) or remnant peat in the Delta's tidal wetlands (37 ± 5.9 kg C m^{-3}) due to impacts of compaction and land-surface subsidence.


Photo by Shira Bezalel, SFEI

FUTURE RESTORATION SCENARIOS

Q2 & Q3: *What is the potential upper bound for GHG benefits and peat carbon accumulation through wetland restoration and rice cultivation in the Delta? What magnitude of GHG emissions reductions and peat carbon storage could existing Delta wetland restoration and rice farming targets achieve?*

We developed five future land use scenarios to assess opportunities for peat carbon accumulation, GHG benefits, and subsidence mitigation through wetland restoration and rice cultivation in the Delta.

FIVE FUTURE SCENARIOS

1. **Reference:** The reference scenario served as a baseline against which alternative scenarios were compared. In this scenario, the current configuration of land uses were maintained into the future.

2. **Maximum potential:** The maximum potential scenario defined the theoretical potential for tidal restoration and subsidence mitigation. In this scenario, all sites at intertidal elevations were converted to tidal wetland, and all subsided areas were converted to subsidence reversal wetlands. Urban and barren areas were excluded from the analysis.

3. **GHG 1:** Focused primarily on GHG mitigation, GHG 1 places 76,500 acres of wetlands managed for subsidence reversal and rice in sites with the highest potential GHG benefit. GHG 1 is based on additional (above current commitments) acres of freshwater wetland in Scenario 1 from California's 2022 Scoping Plan For Achieving Carbon Neutrality (CARB 2022).

4. **GHG 2:** This scenario places 38,100 acres of wetlands managed for subsidence reversal and rice in sites with the greatest potential GHG benefit. GHG 2 is based on the extent of additional freshwater wetlands in the Scoping Plan Scenario 3 (CARB 2022).

5. **GHG-habitat:** Based on the Delta Plan Performance Measures for subsidence reversal and tidal wetland (PM 5.2, 4.12, and 4.16; DSC 2013; DSC 2022), this scenario adds 32,500 acres of tidal wetland and 30,000 acres of subsidence reversal and rice, of which 3,500 acres is at shallowly subsided elevations to enable tidal reconnection.

Table 1. Description of future scenarios targets for tidal wetland, subsidence reversal wetland, and rice cultivation. Subsidence reversal wetlands and rice in GHG 1, GHG 2, and the GHG-habitat scenario were sited to optimize GHG emissions reductions.

FUTURE SCENARIO	LAND COVER TYPE	SCENARIO TARGET
Reference	*Tidal wetland*	*Maintain existing*
	Subsidence reversal wetland	*Maintain existing*
	Rice	*Maintain existing*
Maximum potential	*Tidal wetland*	*Expand to all area at intertidal elevations**
	Subsidence reversal wetland	*Expand to all area at intertidal elevations**
	Rice	*Maintain existing*
GHG 1	*Tidal wetland*	*Maintain existing*
	Subsidence reversal wetland	*Add 42,075 acres (55% of GHG 1 target)*
	Rice	*Add 34,425 acres (45% of GHG 1 target)*
GHG 2	*Tidal wetland*	*Maintain existing*
	Subsidence reversal wetland	*Add 20,955 acres (55% of GHG 2 target)*
	Rice	*Add 17,145 acres (45% of GHG 2 target)*
GHG-habitat	*Tidal wetland*	*Add 32,500 acres at intertidal elevations*
	Subsidence reversal wetland	*Add 16,500 acres (55% of GHG-habitat target), 3,500 of which is at shallowly subsided elevations*
	Rice	*Add 13,500 acres (45% of GHG-habitat target)*

*Excludes land classified as urban or barren

SCENARIO ANALYSIS

- **Modeling timeframe:** We projected scenarios 40 years into the future assuming 1.1 ft of sea level rise (SLR) by 2060, the 50% probabilistic SLR projection for California from the Ocean Protection Council (OPC 2018).

- **Elevation and carbon analyses:** We used three process-based biogeochemical models to predict future elevations, changes in carbon stocks, and net CO_2 emissions or uptake. The Coastal Wetlands Equilibrium Model (CWEM; Morris et al. 2022) predicts vertical accretion in tidal wetlands, SUBCALC[2] (Deverel and Leighton 2010; Deverel et al. 2016b) predicts peat oxidation and subsidence in drained organic soils, and SEDCALC (Callaway et al. 1996; Deverel et al. 2014) predicts elevation gains and peat carbon accumulation in subsidence reversal wetlands.

- **Other GHG analyses:** We used GHG emission factors from the literature to predict methane and nitrous oxide emissions, as well as net CO_2 emissions from other land-use types. For a full description of modeling methods and emission factors, see Vaughn et al. (*submitted*).

- **Landscape Scenario Planning Tool**: All analyses were packaged in a new Carbon and Greenhouse Gas module for the Landscape Scenario Planning Tool. This allowed us to evaluate carbon and GHG outcomes alongside other metrics of ecosystem function relevant to land managers and planners.

Photo by Kate Roberts, SFEI

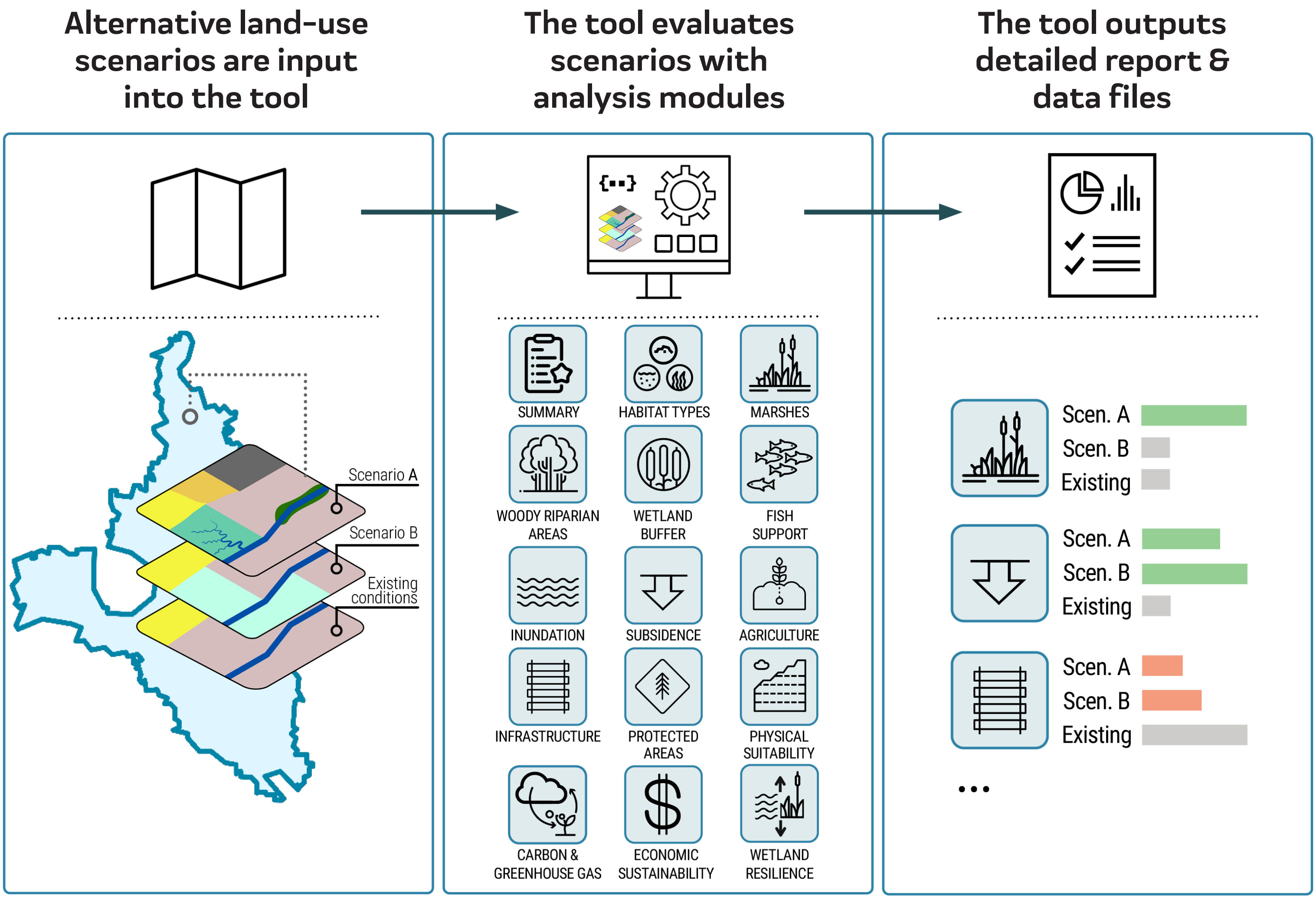


Figure 4. The Landscape Scenario Planning Tool (LSPT) is a GIS-based platform that allows users to compare the effects of Delta land use scenarios on a variety of ecosystem functions. Users input scenarios as GIS layers, and the tool runs a series of quantitative analyses that are grouped by theme into analysis modules. The new Carbon and Greenhouse Gas module outputs metrics of elevation change, carbon storage, and GHG emissions, facilitating comparisons between alternative scenarios relative to baseline conditions. This module also includes a functionality for users to explore potential revenue from the sale of carbon credits.

FUTURE MODELING RESULTS:

POTENTIAL TO MITIGATE SUBSIDENCE AND BUILD ELEVATIONS

Table 2. Extent of land-surface subsidence at the end of the 40-year modeling period

SCENARIO	DEEPLY SUBSIDED LAND AREA (>10 ft below MTL) [acres]	SHALLOWLY SUBSIDED LAND AREA (between MLLW and MTL – 10 ft) [acres]	INTERTIDAL LAND AREA [acres]	TIDAL-TERRESTRIAL LAND AREA (above MHHW) [acres]
Modern Delta (2017)	161,400	130,700	44,200	28,100
Reference	180,100	127,400	38,700	15,900
Maximum potential	129,100	134,400	80,300	18,000
GHG 1	171,700	135,300	39,100	15,900
GHG 2	177,000	130,300	38,700	15,900
GHG-habitat	178,200	127,700	40,100	15,900

Notes: modern scenario reflects the current elevation distribution as of 2017. Intertidal zone approximated using a mean tidal range of 3.6 ft. ***Maximum potential*** *extent excludes 217 acres for which model-based subsidence or accretion values were unavailable.*

Key findings:

REFERENCE

If current land uses continue over the coming four decades, the Delta could see a 19,000-acre increase in deeply subsided land and an 18,000-acre loss of intertidal and tidal-terrestrial elevations due to subsidence and SLR. This shift in elevations would reduce opportunities to restore tidal habitat and increase the risk of levee failures due to increased hydrostatic forces and intensified seepage (Deverel et al. 2016a).

MAXIMUM POTENTIAL

Delta-wide wetland restoration has the potential to dramatically reduce the extent of deeply subsided land and increase opportunities for tidal reconnection by building elevations in shallowly subsided sites.

GHG 1, GHG 2, GHG-HABITAT

The GHG 1, GHG 2, and GHG-habitat scenarios offer elevation benefits relative to Reference-scenario conditions. Given ongoing subsidence in non-wetland sites, however, the extent of deeply subsided land is expected to increase over time in all three scenarios. Similar opportunities and challenges exist at intertidal elevations. By restoring 32,500 acres at intertidal or near-intertidal elevations the GHG-habitat scenario increases intertidal land area relative to the Reference scenario. However, even this scenario sees an absolute loss of area at intertidal elevations over the coming 40 years due to accelerating SLR.

POTENTIAL TO REDUCE OR REVERSE FUTURE PEAT CARBON LOSSES

MAXIMUM POTENTIAL

We found that as much as 24 MMT of carbon could theoretically be sequestered with Delta-wide wetland restoration.

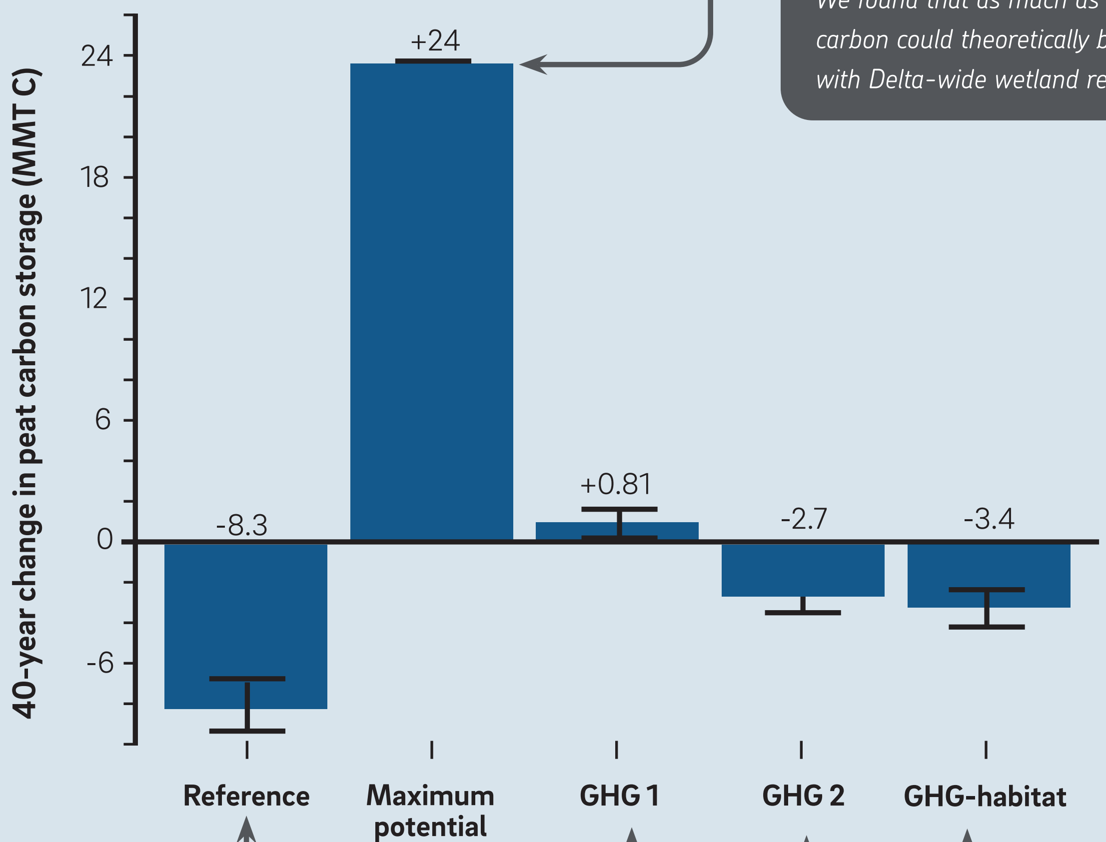


Figure 5. Future scenario cumulative change in peat carbon storage over the 40-year modeling period. Error bars represent standard errors propagated from error ranges from SUBCALC[2], CWEM, and peat core data.

REFERENCE

If existing land uses are maintained, the Delta could lose an estimated 8.3 MMT carbon over four decades due to ongoing subsidence, with as much as 1m of elevation loss on the most rapidly subsiding islands. This loss of 8.3 MMT of C is comparable to clear-cutting more than 100,000 acres of U.S. forest (EPA 2021).

GHG 1, GHG 2, GHG-HABITAT

All restoration scenarios sequester carbon in wetland sites and reduce overall carbon losses, but ambitious subsidence mitigation is needed to turn the Delta to a net carbon sink.

HIGH REFERENCE SCENARIO GHG EMISSIONS

Under reference scenario conditions, we found that the Delta will emit an estimated 1.2 MMT CO_2 equivalents (CO_2e) per year to the atmosphere. Modeled per-acre GHG emissions depended on land use type, water table depth, soil organic matter content, and other site-specific factors. Across the Delta, sites ranged from a weak net sink for GHGs to a net source as high as ~25 MT CO_2e per acre per year.

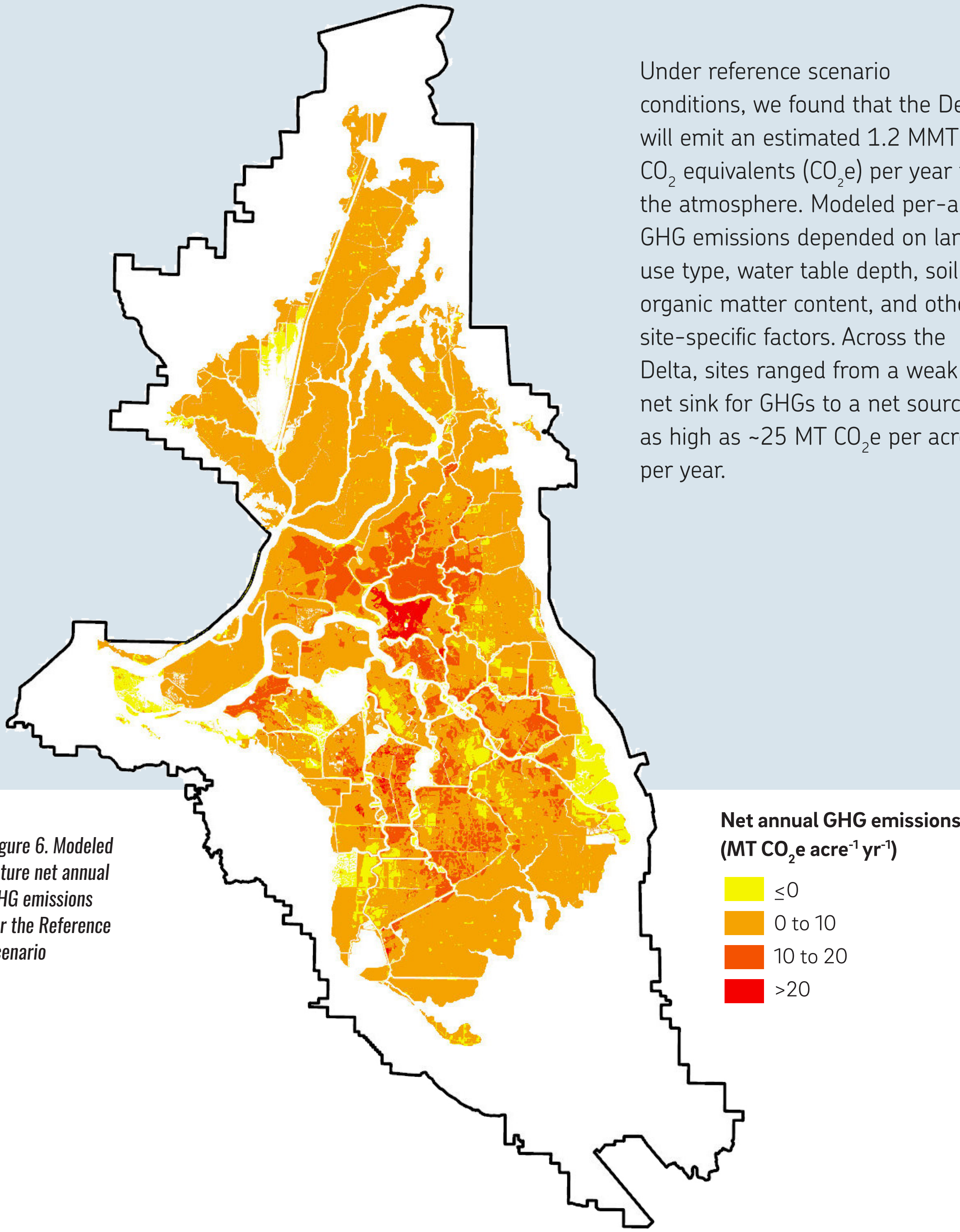
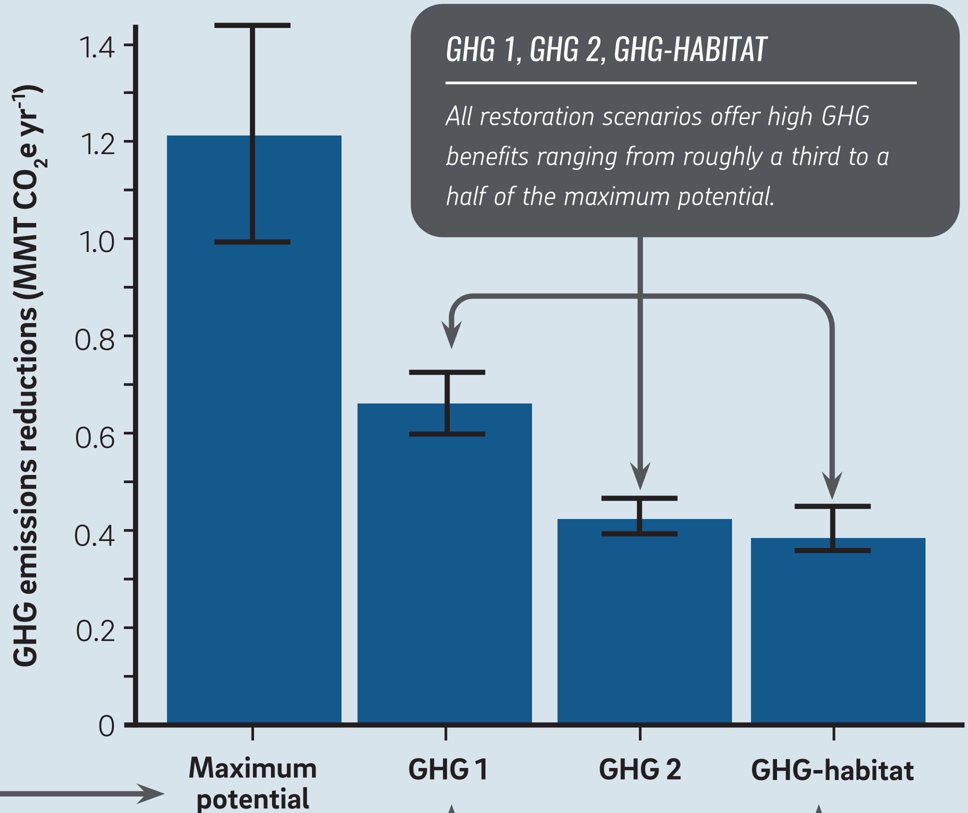


Figure 6. Modeled future net annual GHG emissions for the Reference scenario

LARGE REDUCTIONS IN GHG EMISSIONS IN WETLAND RESTORATION SCENARIOS



GHG 1, GHG 2, GHG-HABITAT

All restoration scenarios offer high GHG benefits ranging from roughly a third to a half of the maximum potential.

MAXIMUM POTENTIAL

The maximum potential scenario would provide GHG emissions reductions of 1.2 MMT CO_2e yr^{-1}, converting the Delta from a large GHG source to roughly carbon neutral. Achieving an equivalent GHG benefit by planting trees would require planting roughly more than 2 million trees each year, year after year (EPA 2022).

GHG 1 & GHG-HABITAT

GHG 1 and GHG-habitat restore similar acres of wetlands, but provide substantially different GHG emissions reductions. This difference highlights the impact of alternative objectives. GHG 1 focused exclusively on GHG benefits, with all wetlands placed in sites with the highest baseline emissions. GHG-habitat, in contrast, prioritized both GHG benefits and tidal habitat, with over half the additional wetlands at intertidal or near-intertidal elevations where baseline GHG fluxes are lower.

Figure 7. Future scenario greenhouse gas emissions reductions. Net GHG emissions reductions were calculated as the mean annual difference in GHG emissions between the Reference scenario and each alternative scenario over the 40-year modeling period. Units of CO_2 equivalents (CO_2e) incorporate net exchanges of CO_2, methane, and nitrous oxide.

MULTIPLE BENEFITS FOR ECOSYSTEMS AND PEOPLE

Q4: *How can the configuration of wetland restoration and rice cultivation be optimized for GHG mitigation and other restoration goals?*

In addition to carbon and GHG benefits, the scenarios we analyzed offer a variety of other benefits for ecosystems and people. Restoring wetlands in the Delta supports fish, birds, and other wildlife populations, particularly when configured in large marsh patches that enhance connectivity between wetlands and open water. Creation of wetlands for subsidence mitigation also protects the region's infrastructure and economy. Without such measures, elevation losses due to continued subsidence and rising sea levels will exacerbate strain on levees, increasing pumping costs and the risk of catastrophic levee failures (Deverel et al. 2016a). At the same time, however, implementing scenario land use changes presents financial challenges and may entail tradeoffs with existing land uses. Because the majority of deeply subsided land in the central Delta is in private ownership, there is a need to identify near-term solutions that can mitigate subsidence while providing reasonable income. Converting drained agriculture to rice is one such solution, as rice offers sustained farm income while reducing GHG emissions and halting subsidence by maintaining saturated soils for much of the year (Hatala et al. 2012; Knox et al. 2015; Deverel et al. 2016b). Impounded nontidal wetlands can also provide income on the voluntary carbon market.

Table 3 shows examples of metrics evaluated by the LSPT, enabling comparisons among scenarios across a number of different functions.

Key takeaways:

- Subsidence mitigation reduces the likelihood of future levee failures (Deverel and Leighton 2010). In the most rapidly subsiding sites, we modeled elevation benefits of as much as 2 m relative to the reference scenario. This could be particularly relevant in areas that are becoming too wet to farm (Deverel et al. 2015).
- Wetland restoration increases wildlife habitat extent and habitat quality, for instance by creating large patches that are likely to develop complex channel networks (Robinson et al. 2014).
- Connectivity between water and wetlands is particularly important for fish such as salmonids (SFEI-ASC 2020). By increasing tidal wetland area, the GHG-habitat scenario in particular improves metrics of habitat connectivity.
- Wetland creation presents tradeoffs with existing agricultural uses, but rice cultivation and the sale of carbon credits have the potential to replace lost income while reducing subsidence and GHG emissions (Whipple et al. 2022). Using a conservative carbon price of $10/ton, we estimated about three million dollars in potential carbon revenue for the GHG-habitat scenario.

Photo by Kate Roberts, SFEI

Table 3. Additional metrics of ecosystem function and land use associated with future scenarios. The Reference and Maximum potential scenarios bracket the range of potential values for each metric (row) in the table. Green highlighting indicates which of the three other future scenarios, GHG 1, GHG 2, and GHG-habitat, performs best for a given metric.

METRIC	RANGE OF POTENTIAL VALUES (Reference - Maximum potential)	GHG 1	GHG 2	GHG-HABITAT
Area of deeply subsided land (>10 ft below MTL)	180,120 - 129,846 acres	171,058 acres	176,790 acres	177,982 acres
Area of tidal and nontidal marsh patches greater than 100 ha (247 acres)	11,876 - 390,873 acres	41,201 acres	25,392 acres	44,079 acres
Area of tidal and nontidal marsh patches greater than 500 ha (1,236 acres)	2,116 - 389,791 acres	12,792 acres	7,037 acres	17,169 acres
Average distance to nearest tidal and nontidal marsh patch greater than 100 ha (247 acres)	8.0 - 0.84 miles	2.4 miles	3.5 miles	1.9 miles
Area of tidal marsh within 2 km (1.24 mi) of open water	11,457 - 23,223 acres	11,457 acres	11,457 acres	12,486 acres
Average distance to nearest large connected wetland	4.3 - 0.027 miles	4.3 miles	4.3 miles	4.2 miles
Loss of agriculture	0 - 283,712 acres	38,841 acres	19,771 acres	45,082 acres
Loss of prime farmland	0 - 241,337 acres	33,044 acres	18,143 acres	36,725 acres

Notes: metrics presented here were quantified with the LSPT, using the Carbon and Greenhouse Gas, Marshes, Fish Support, and Agriculture analysis modules. Marsh patches are defined as contiguous regions of tidal and non-tidal emergent wetland. Hydrologically connected wetlands are defined as contiguous with the channel network. Prime farmland grade is defined by the California Department of Conservation's Farmland Mapping and Monitoring Program's 2018 database (https://www.conservation.ca.gov/dlrp/fmmp)

Photo by Kate Roberts, SFEI

Photo by Shira Bezalel, SFEI

CONCLUSIONS

- The sooner action is taken to mitigate subsidence, restore ecosystems, and reduce ongoing GHG emissions from Delta soils, the greater the opportunities for a resilient Delta ecosystem, economy, and water supply, and the greater the Delta's contributions to California's climate change mitigation goals.
- Large-scale wetland creation/restoration and rice fields have the potential to mitigate subsidence, reduce or reverse peat carbon losses, and reduce GHG emissions.
- The scale of opportunity for GHG mitigation is LARGE (1.2 MMT CO_2e per year), setting the context for ambitious land-use planning in the Delta.
- Competing priorities in restoration planning call for a balanced portfolio that considers stressors to the climate, wildlife, and the Delta's infrastructure and economy. Such a balanced portfolio should mitigate subsidence and GHG emissions through rice and managed wetlands, and maintain current tidal marsh and restore tidal habitat in areas resilient to moderate SLR.
- Subsidence mitigation calls for both near-term and long-term solutions. In the near term, conversion to rice in the most rapidly subsiding areas can mitigate elevation losses while providing sustained income. Over the longer term, projected increases in carbon prices and the financial benefits of reducing the risk of levee failure may be sufficient to incentivize larger scale conversion to subsidence reversal and tidal wetlands.
- Multi-benefit tools like the Landscape Scenario Planning Tool can help land use planners evaluate large-scale opportunities, impacts, and tradeoffs across a range of critical ecosystem functions.

RESOURCES & RELATED EFFORTS

Download the Landscape Scenario Planning Tool (LSPT): The maps created in this effort are available for conservation planners to use in the LSPT. The LSPT is a set of resources to assist users with developing, analyzing, and evaluating different land use scenarios in California's Suisun-Delta region. The tool is designed to inform ongoing and future restoration planning efforts by assessing how proposed projects will affect a suite of landscape metrics relating to desired ecosystem functions and services. Maps from this study are incorporated into the newly added wetland resilience module.

Access the full report: More details on the methods and findings of this study can be found in the published journal article (manuscript submitted for publication).

- Vaughn L, Deverel S, Panlasigui S, Drexler J, Olds M, Dia J, Harris K, Morris J, Grenier L, Robinson A, Ball D. submitted. Marshes and farmed wetlands can build resilience in the Sacramento-San Joaquin Delta: quantification of potential greenhouse gas and subsidence mitigation benefits.

Read the other reports from the Blue Carbon and Wetland Resilience Project: This study is part of a larger project that looked at carbon sequestration and wetland resilience in the Delta. The following resources provide more information on the other studies in this project.

Published journal articles:

- Robinson A, Harris K, Morris J, McKnight K, Vaughn L, Safran S, Panlasigui S, Grenier L, Ball D. submitted. Spatial patterns in wetland resilience in the Sacramento-San Joaquin Delta.

- Morris JT, Drexler J, Vaughn LS, Robinson A. 2022. An assessment of future tidal marsh resilience in the San Francisco Estuary through modeling and quantifiable metrics of sustainability. Front Environ Sci. 2384.

Summary report of Robinson et al. (2022):

- [SFEI-ASC] San Francisco Estuary Institute-Aquatic Science Center. 2022. Delta Wetland Futures: Tidal Marsh Resilience to Sea Level Rise. Richmond (CA): San Francisco Estuary Institute. Publication No. 1106

REFERENCES

Anthony TL, Silver WL. 2020. Mineralogical associations with soil carbon in managed wetland soils. Glob Change Biol. gcb.15309. https://doi.org/10.1111/gcb.15309

Callaway JC, Borgnis EL, Turner RE, Milan CS. 2012. Carbon Sequestration and Sediment Accretion in San Francisco Bay Tidal Wetlands. Estuaries Coasts. 35:1163–1181. https://doi.org/10.1007/s12237-012-9508-9

Callaway JC, Nyman JA, DeLaune RD. 1996. Sediment accretion in coastal wetlands: a review and a simulation model of processes. Curr Top Wetl Biogeochem. 2:23.

[CARB] California Air Resources Board. 2022. 2022 Scoping Plan for Achieving Carbon Neutrality. Available from: https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan/2022-scoping-plan-documents

Craig MS, Kundariya N, Hayashi K, Srinivas A, Burnham M, Oikawa P. 2017. Geophysical surveying in the Sacramento Delta for earthquake hazard assessment and measurement of peat thickness. In AGU Fall Meeting Abstracts, vol. 2017, pp. T23G-07. 2017.

Deverel S, Ingrum T, Lucero C, Hydrofocus, Inc., Drexler J, U.S. Geological Survey. 2014. Impounded Marshes on Subsided Islands: Simulated Vertical Accretion, Processes, and Effects, Sacramento-San Joaquin Delta, CA USA. San Francisco Estuary Watershed Sci. [accessed 2019 November 08];12:. https://doi.org/10.15447/sfews.2014v12iss2art5

Deverel S, Leighton DA. 2010. Historic, Recent, and Future Subsidence, Sacramento-San Joaquin Delta, California, USA. San Francisco Estuary Watershed Sci. [accessed 2019 November 12];8:. https://doi.org/10.15447/sfews.2010v8iss2art1

Deverel SJ, Bachand S, Brandenberg SJ, Jones CE, Stewart JP, Zimmaro P. 2016a. Factors and Processes Affecting Delta Levee System Vulnerability. San Francisco Estuary Watershed Sci. [accessed 2019 November 08];14:.Drexler JZ, de Fontaine CS, Brown TA. 2009a. Peat Accretion Histories During the Past 6,000 Years in Marshes of the Sacramento-San Joaquin Delta, CA, USA. Estuaries Coasts Port Repub. 32:871–892. http://dx.doi.org.libproxy.berkeley.edu/10.1007/s12237-009-9202-8

Deverel SJ, Dore S, Schmutte C. 2020. Solutions for subsidence in the California Delta, USA, an extreme example of organic-soil drainage gone awry. Proc Int Assoc Hydrol Sci. 382:837–842.

Deverel SJ, Ingrum T, Leighton D. 2016b. Present-day oxidative subsidence of organic soils and mitigation in the Sacramento-San Joaquin Delta, California, USA. Hydrogeol J. 24:569–586.

Deverel SJ, Lucero CE, Bachand S. 2015. Evolution of Arability and Land Use, Sacramento–San Joaquin Delta, California. San Francisco Estuary Watershed Sci. [accessed 2020 June 18];13:. https://doi.org/10.15447/sfews.2015v13iss2art4

Drexler JZ, de Fontaine CS, Brown TA. 2009a. Peat Accretion Histories During the Past 6,000 Years in Marshes of the Sacramento-San Joaquin Delta, CA, USA. Estuaries Coasts Port Repub. 32:871–892. http://dx.doi.org.libproxy.berkeley.edu/10.1007/s12237-009-9202-8

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

Drexler JZ, Khanna S, Lacy JR. 2021. Carbon storage and sediment trapping by Egeria densa Planch., a globally invasive, freshwater macrophyte. Sci Total Environ. 755:142602.

Drexler JZ, Khanna S, Schoellhamer DH, Orlando J. 2019. A Blue Carbon Primer. CRC Press. pp. 307–325.

[DSC] Delta Stewardship Council. 2013. The Delta Plan - ensuring a reliable water supply for California, a healthy Delta ecosystem and a place of enduring value.

[DSC] Delta Stewardship Council. 2022. Delta Plan Chapter 4. Protect, Restore, and Enhance the Delta Ecosystem. Amended June 2022. Available from: http://deltacouncil.ca.gov/pdf/delta-plan/2019-11-21-preliminary-draft-delta-plan-chapter-4.pdf

DWR and USGS. 2019. LiDAR Data for the Sacramento-San Joaquin Delta and Suisun Marsh.

[EPA] United States Environmental Protection Agency. 2021. Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2019. Washington, D.C.: United States Environmental Protection Agency. Available from: https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf

[EPA] United States Environmental Protection Agency. 2022. Greenhouse Gas Equivalencies Calculator, updated March 2022. Available from: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

Hatala JA, Detto M, Sonnentag O, Deverel SJ, Verfaillie J, Baldocchi DD. 2012. Greenhouse gas (CO2, CH4, H2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. Agric Ecosyst Environ. 150:1–18. https://doi.org/10.1016/j.agee.2012.01.009

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

Knox SH, Sturtevant C, Matthes JH, Koteen L, Verfaillie J, Baldocchi D. 2015. Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO2 and CH4) fluxes in the Sacramento-San Joaquin Delta. Glob Change Biol. 21:750–765. https://doi.org/10.1111/gcb.12745

Miller RL, Fram M, Fujii R, Wheeler G. 2008. Subsidence Reversal in a Re-established Wetland in the Sacramento-San Joaquin Delta, California, USA. San Francisco Estuary Watershed Sci. [accessed 2021 May 12];6:. https://doi.org/10.15447/sfews.2008v6iss3art1

Morris JT, Drexler J, Vaughn LS, Robinson A. 2022. An assessment of future tidal marsh resilience in the San Francisco Estuary through modeling and quantifiable metrics of sustainability. Front Environ Sci. 2384.

Mount J, Twiss R. 2005. Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta. San Francisco Estuary Watershed Sci. 3:.

[OPC] Ocean Protection Council. 2018. State of California Sea-Level Rise Guidance: 2018 Update. Ocean Prot Counc Sacramento, CA USA. 84:.

Robinson AH, Safran SM, Beagle J, Grossinger RM, Grenier JL, Askevold RA. 2014. A Delta Transformed: Ecological Functions, Spatial Metrics, and Landscape Change in the Sacramento-San Joaquin Delta. Richmond, CA: San Francisco Estuary Institute - Aquatic Science Center. Available from: http://sfei.org/projects/delta-landscapes-project

[RMA] Resource Management Associates. 2015. Hydrodynamic and Salt Transport Modeling of the Pre-Development Upper San Francisco Estuary, Phase 2 Technical Memorandum Prepared for the Metropolitan Water District of Southern California. Resource Management Associates.

[SFEI-ASC] San Francisco Estuary Institute-Aquatic Science Center. 2020. Identifying Suitable Rearing Habitat for Chinook Salmon in the Sacramento-San Joaquin Delta. Publication #972. Richmond, CA: San Francisco Estuary Institute.

Vaughn LJS, Deverel SJ, Panlasigui S, Drexler JZ, Olds MA, Diaz JT, Harris KF, Morris J, Grenier JL, Robinson AH, Ball DA. Submitted. Marshes and farmed wetlands can build resilience in the Sacramento-San Joaquin Delta: quantification of potential greenhouse gas and subsidence mitigation benefits.

Whipple AA, Safran SM, Zeleke D, Wells E, Deverel S, Olds M, Cole S, Rodriguez-Flores J, Guzman A, Medellin-Azuara J, Grenier JL. 2022. Resilient Staten island: Landscape Scenario Analysis Pilot Application. Prepared for the U.S. Fish and Wildlife Service. SFEI Publication #1079. Richmond, CA: San Francisco Estuary Institute.