RESILIENT STATEN ISLAND:
Landscape Scenario Analysis Pilot Application

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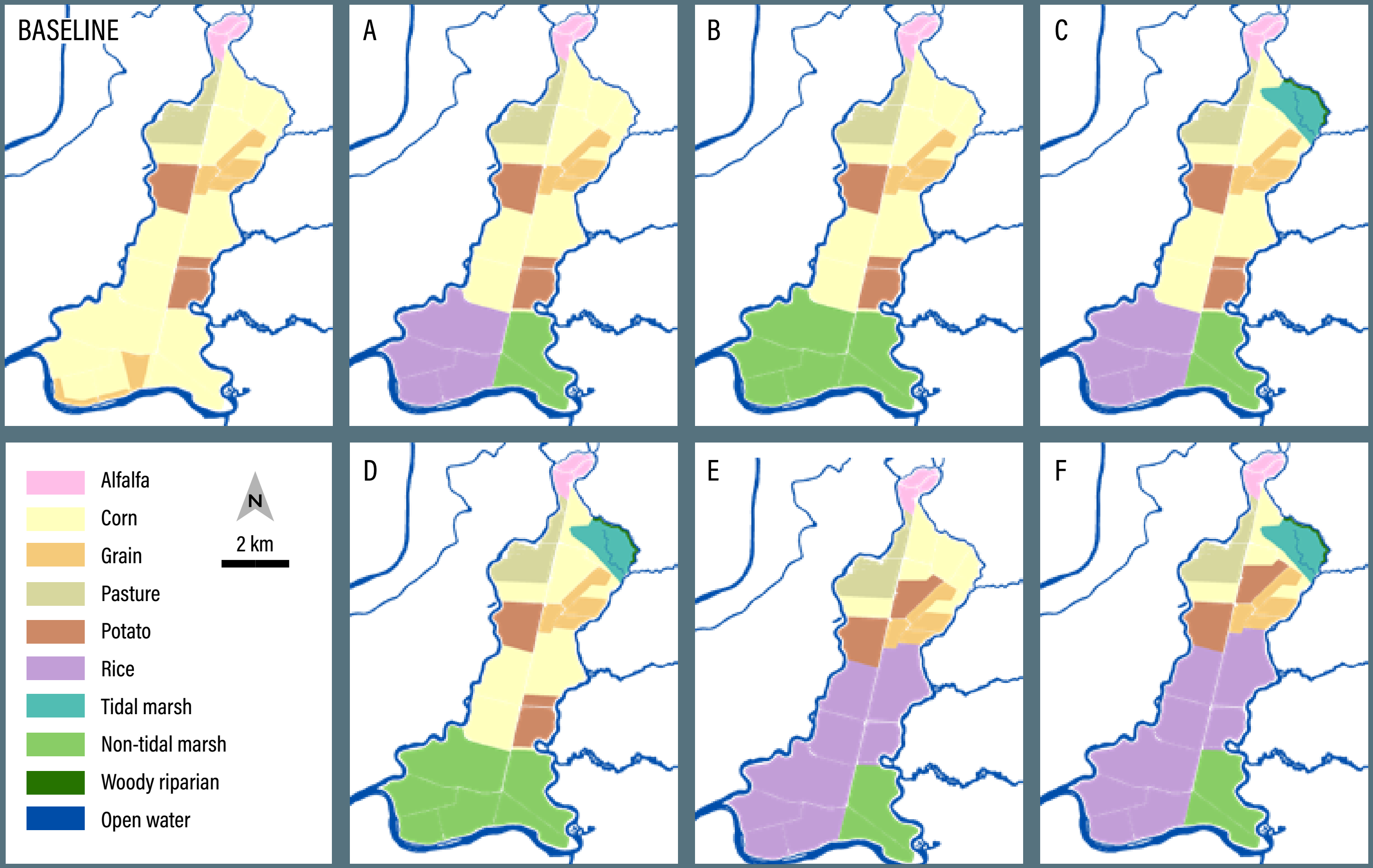
Overview

A central motivating question for the Sacramento-San Joaquin Delta science and management community is what should be done, where and when, to support future Delta landscapes that are ecologically and economically viable and resilient to change. Actions must be taken that have the greatest potential for achieving multiple benefits. This is especially important given the urgency to rapidly transition Delta landscapes to address biodiversity loss, erosion of ecosystem resilience, flood risk, water supply reliability, and cultural and economic sustainability. Landscape-scale planning is needed to examine how individual actions add up to meaningful change. Such planning involves figuring out how different areas can provide different functions at different times and helps show how choices made now can help shift trajectories toward desired outcomes. Too often, land use and management decisions are made based on a limited set of objectives or at the site scale, resulting in missed opportunities. Actions (or inaction) should not foreclose on critical opportunities. Moving forward, there is great need to more effectively compare possible future scenarios across a range of ecological and economic factors. This scenario analysis for Staten Island — a large Delta island managed for multiple uses and facing challenges similar to elsewhere in the Delta — provides an approach to help address this need.



Staten Island baseline (2014 land use) and restoration and land use scenarios (A–F) evaluated for this pilot application to compare scenarios across multiple metrics related to ecosystem, land elevation, greenhouse gas emissions reductions, and economics.

Motivation for the approach

- To enact change, clearer visions of future Delta landscapes are needed to incentivize land use and management changes required for a more sustainable future that supports healthy ecosystems, climate goals, and an agricultural economy.
- Multi-benefit planning to support rapid transitioning to a Delta landscape that has more sustainable land uses and a healthier ecosystem, while supporting an agricultural economy and the Delta as place.
- Planning to examine benefits over the long term to help initiate actions that will use natural processes to increase resilience over time and avoid missing future opportunities.
- Landscape-scale planning to allow for maximizing overall benefits, where land uses are matched to their appropriate physical locations and different functions are provided in different locations and at different times.
- A transparent science-based approach can provide a common basis for future landscape visions.

Findings

- Integrating existing approaches supports evaluation of scenarios across a range of ecological and economic costs and benefits.
- Various land uses and management actions are needed to maximize benefits at the landscape scale.
- No single scenario maximizes all benefits. Multi-benefit planning in complex landscapes inherently involves tradeoffs.
- Opportunities to reverse (or halt) subsidence should be taken now.
- Scenarios with tidal marsh show the greatest ecosystem benefits overall, particularly if paired with rice to support wintering Sandhill Cranes.
- Scenarios with marsh (managed and tidal) improve overall connectivity between marsh patches in the Delta.
- Key factors affecting carbon and net GHG emissions reductions are degree of subsidence, soil organic matter content, and current land use.
- Marsh (managed and tidal) on peat soils provide the greatest subsidence reversal and net GHG emissions reductions.
- Scenarios with rice and marsh reduce peat loss by 91%-195% and reduce net GHG emissions by 31-51% over a 50-year period relative to baseline.
- Including rice provides some subsidence and GHG emissions benefits while helping to offset revenue losses from managed and tidal marsh.
- More rigorous evaluation of uncertainty and a wider array of costs and benefits of land use management would improve this analysis.
- When envisioning a future resilient Delta, integrated analytical approaches help address the many complexities and interdependencies.

Group	Metric Category	Scenario					
		A	B	C	D	E	F
Ecosystem	Marsh ecosystem support	🟦	🟦	🟦	🟦 ✓	🟦	🟦
	Aquatic ecosystem support	🟦	🟦	🟦 ✓	🟦 ✓	🟦	🟦 ✓
	Crane habitat	🟨	🟨	🟨	🟨		🟨
Inundation	Hydrologic connectivity			🟦 ✓	🟦 ✓		🟦 ✓
Land elevation	Wetted extent	🟦	🟦	🟦	🟦	🟦	🟦 ✓
	Net volume change 2014-2064	🟦	🟦	🟦	🟦 ✓	🟦	🟦
Carbon	GHG cumulative emissions 2014-2064	🟦	🟦	🟦	🟦	🟦	🟦 ✓
Economic	Annual net revenue	🟦	🟨	🟦	🟨	🟦 ✓	🟦

Summary of scenario comparison outcomes relative to baseline across categories of metrics. Blue represents improvement and yellow reduction. Checks indicate the greatest improvement.

INTRODUCTION

Tidal and floodplain wetland landscapes are hotspots for biodiversity that store carbon and provide other essential ecosystem services related to flood risk reduction, water supply, food security, and recreation. They are also some of the most threatened and degraded ecosystems globally, highly altered by agriculture and urban development. These systems have been largely disconnected from natural processes, causing habitat loss as well as subsidence due to drainage and oxidation of organic soils. The disturbance and drainage of wetlands also substantially contributes to global greenhouse gas (GHG) emissions. How land is managed into the future will be an important factor in meeting targets for climate change mitigation and adaptation (Griscom et al., 2017). The disconnection and alteration of tidal and floodplain wetland ecosystems has meant that many of these landscapes are no longer able to sustain important ecological functions and human benefits. Combined with eroded resilience to change, they face increasing threats from continued subsidence as well as sea level rise and flooding due to climate change.

The Sacramento-San Joaquin Delta (Delta) of California is an inverted or inland delta, where two major river systems meet in a complex of tidal channels and then flow through the narrow Carquinez Straight before entering the San Francisco Bay to the Pacific Ocean. Historically, the Delta consisted of nearly 150,000 ha of freshwater tidal marsh and over 1,500 km of tidal channels, along with an additional 62,000 ha of perennial marsh and riparian forests occupying the floodplains and flood basins connected to the tidal portion of the Delta (Whipple et al., 2012). The historical Delta supported diverse and productive ecosystems (Whipple et al., 2012, Cloern et al., 2021). The Delta is now an agricultural landscape, with over 200,000 ha of farmland protected by over 1,800 km of levees, and critical to California's water supply system. Habitat loss and other stressors have degraded ecosystem functions and threatened native wildlife populations. The Delta is also severely subsided due primarily to oxidation of the Delta's organic peat soils associated with drainage and agriculture, with some elevations on Delta islands more than 8 m below sea level. An estimated 2.5 billion m^3 of peat soils have been lost, and subsidence continues where peat soils are drained (Mount and Twiss, 2005). This is a major contributor to GHG emissions in the Delta. Subsidence also puts pressure on fragile levees that help direct freshwater supply for much of California and increases pumping costs. Accelerated sea level rise and increased extreme floods under climate change further exacerbate risk of island flooding. The current system is increasingly less able to respond to disturbances and most current land uses are rapidly becoming less ecologically and economically viable, perpetuating subsidence and carbon emissions while offering limited ecological benefits.

There is recognized urgency for change to improve ecosystem health, increase water supply reliability, reverse or halt subsidence, reduce emissions, and sequester carbon, while maintaining viable economies that support Delta communities and unique culture (Delta Stewardship Council, 2013). To enact change, clearer visions of future Delta landscapes are needed to incentivize the land use and management changes required for a more sustainable future that supports healthy ecosystems, climate goals, and an agricultural economy. These visions must reflect current physical constraints and opportunities, and in many cases may require adaptation pathways, where different actions are taken over time as conditions change. Critically, these visions should articulate how restoration and management actions can achieve multiple benefits at the landscape scale. This can help bridge gaps between decision-making at the local farm level and the Delta-wide goals.

Staten Island, a large 3,700 ha Delta island, offers an opportunity to explore how land use changes and management beyond the agricultural field scale can be employed to address ecosystem, carbon and economic objectives. It is physically representative of many areas in the Delta, grading from deeply to minimally subsided land. As a subsided island under agricultural production on primarily peat soils, it has been estimated to emit more than 100,000 metric tons of carbon and subside up to 2 cm per year (HydroFocus, Inc, 2012). Owned by a single entity, Staten Island can be managed in a more easily coordinated way than islands with multiple landowners. The Nature Conservancy, as the owner, has already begun shifting to more sustainable management approaches. These help support wildlife (namely management to support wintering Sandhill Cranes) and minimize or reverse subsidence, including recent conversion to rice in some areas with plans for expansion as well as establishment of new managed non-tidal marsh.

The goal of this effort is to demonstrate how scenarios can be used to plan for a future landscape that is ecologically resilient and economically sustainable over the long-term. Future scenarios for Staten Island were assessed with metrics representing a range of costs and benefits associated with different land uses. Specifically, the analysis examined benefits and tradeoffs of land use scenarios across multiple metrics relating to ecosystem functions, subsidence reversal, GHG emissions reduction, and economic revenue. Thus, this project demonstrated how existing tools, methods, and on-the-ground knowledge of Staten Island management can be leveraged to execute a multi-benefit scenario analysis. As a pilot approach, this effort is intended to provide a model for other visioning processes elsewhere in the Delta, illustrate the value of multi-benefit scenario planning, inspire the use and integration of available tools and methods, and to help identify needs for additional research to address uncertainties. This effort builds on years of prior work by project collaborators (e.g., HydroFocus, Inc, 2012; Medellín-Azuara et al., 2014; SFEI-ASC, 2016; Deverel et al., 2017).

Photo by California Department of Water Resources

LANDSCAPE PATTERNS: HISTORICAL AND CURRENT CONDITIONS

Landscape patterns of the Delta prior to substantial Euro-American modifications reflected natural physical gradients (Whipple et al. 2012). At the Delta mouth, vegetation communities shifted along the gradient between saline and brackish tidal to freshwater tidal environments. Moving upstream to the north and south, riverine influences became more dominant, where floods created dynamic habitat mosaics through erosion and deposition, added inorganic sediment to floodplain soils, and built up natural levees along river channels. Positioned between two branches of the Mokelumne River, Staten Island falls along a gradient with tidal conditions dominant at its south end and riverine conditions dominant at its north end (Figure 1). Along the north end of the island, natural levees above tidal extent historically supported dense riparian forest, and as natural levee elevations gradually fell to tide level downstream, vegetation shifted to scattered willow and then to emergent wetland (marsh). The interior of the island was formerly occupied by tidal freshwater marsh (~3,700 ha), with several major branching tidal channel networks extending into the marsh (~36 km). The depth of peat soils was greatest in the southern portion of the island. Organic content was lower in the northern portion, given that tides had more recently transgressed toward the outer extent of the Delta and riverine deposits of inorganic sediment were periodically laid down by floods.

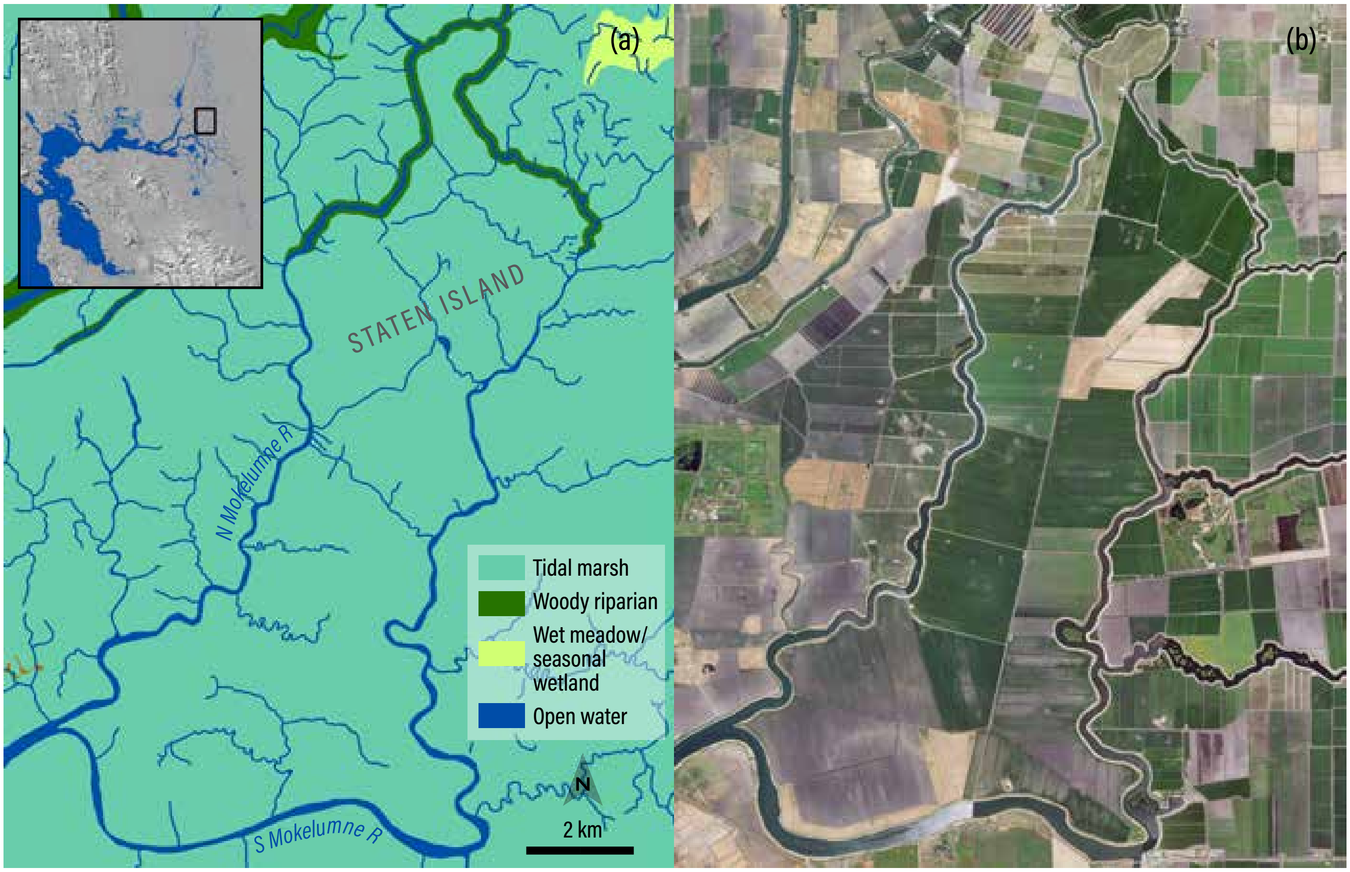


Figure 1. Staten Island within the Sacramento-San Joaquin Delta. The historical (ca. 1800) habitat type map in (a) shows tidal marshes intersected by tidal channels and bordered on the north end by riparian forest (Whipple et al., 2012). Imagery in (b) shows the present-day agricultural landscape (USDA 2014).

Natural physical processes and landscape gradients are largely still present in the channels around the island under current conditions. Water levels in the channels bordering the island still rise and fall with the tides, and floods, though reduced in magnitude and frequency due to damming of the Mokelumne River, still pass downstream with high flows and sediment, largely from the undammed Cosumnes River upstream. However, since the 1860s, human modifications for agriculture have disconnected Staten Island from both tidal and riverine processes and caused substantial subsidence. Land surface elevations range from 0 to 5 m below sea level, with a gradient from deeply to minimally subsided land from south to north (Figure 2a). To regain elevation to sea level with managed marsh (via accumulation of organic matter) would take from 150-200 years in the most deeply subsided southern parts to less than 50 years in the northern parts. The subsidence follows the gradient of organic to more inorganic soils south to north (Figure 2b). The greater peat soil depths in the southern part of the island have led to greater oxidation (and thus subsidence). The agricultural crops grown are annuals, primarily corn. In 2014, corn (2,476 ha), potatoes (327 ha), grain (313 ha), pasture (233 ha), and alfalfa (85 ha) were the main crops on Staten Island. Under the ownership of The Nature Conservancy and management by Conservation Farms and Ranches, the island is now farmed with more sustainable and wildlife friendly practices, with a commitment to converting land use to rice or managed marsh on its peat soils.

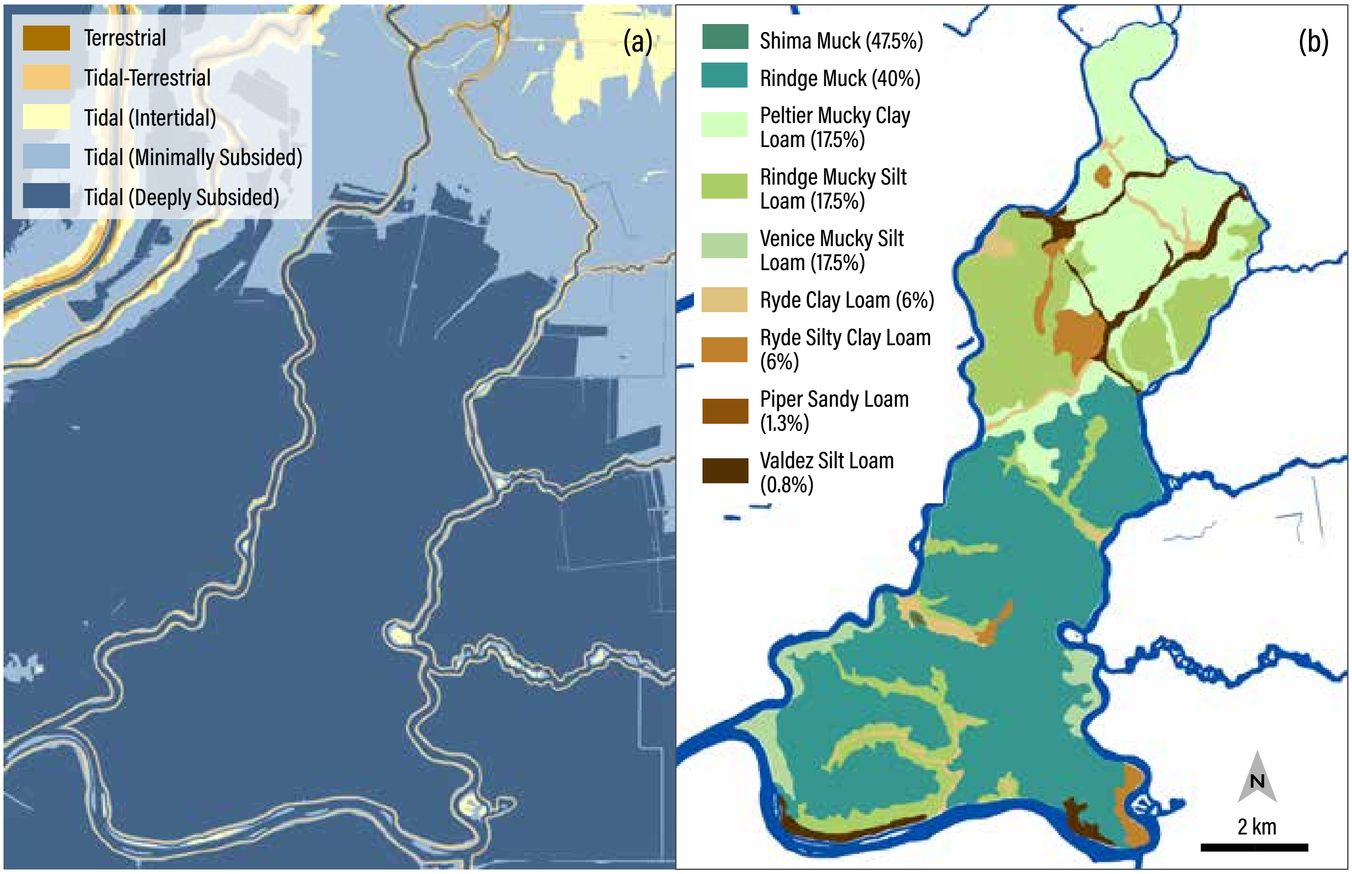


Figure 2. Physical conditions on Staten Island, CA. In (a), geomorphic zones based elevation relative to sea level show that Staten grades from deeply subsided (> 2.4 m below MLLW) to minimally subsided (2.4 m below MLLW to MLLW), north to south. Dominant soil types and their percentage organic content (in parentheses) are shown in (b), with more organic soils in the southern part of the island.

SCENARIO DEVELOPMENT

To facilitate visions of a resilient future Delta, this analysis compared different land use scenarios for Staten Island. With evaluation performed at the scale of the whole island, this pilot study demonstrates a landscape-scale approach to address multiple objectives related to ecosystem health, subsidence and GHG emissions reduction, and economic viability. A mosaic of different land uses and management actions is needed to maximize these multiple benefits. The overarching goal in developing the scenarios was to increase the area of land uses that keep soils wet to limit peat oxidation and subsidence and confer ecological value, while maintaining or improving net revenues.

Six scenarios were used to explore different extents and configurations of wetted land uses (rice, managed non-tidal marsh, or tidal marsh) along with the crops traditionally grown on Staten Island (Figure 3). The potential future scenarios were compared to baseline conditions, derived from 2014 agricultural mapping (Land IQ, 2020). In developing the scenarios, rice and marsh (managed and tidal) were preferentially placed in the southern and central portions of the islands, where the organic soils are most susceptible to subsidence and GHG emissions. All scenarios included approximately 400 ha of managed marsh in the southeastern corner of the island, as planning is currently underway for a managed marsh project in this location. An additional 900 ha of managed marsh was included in Scenarios B and D. Four scenarios included rice, with 900 ha in Scenarios A and C and 1,800 ha in Scenarios E and F.

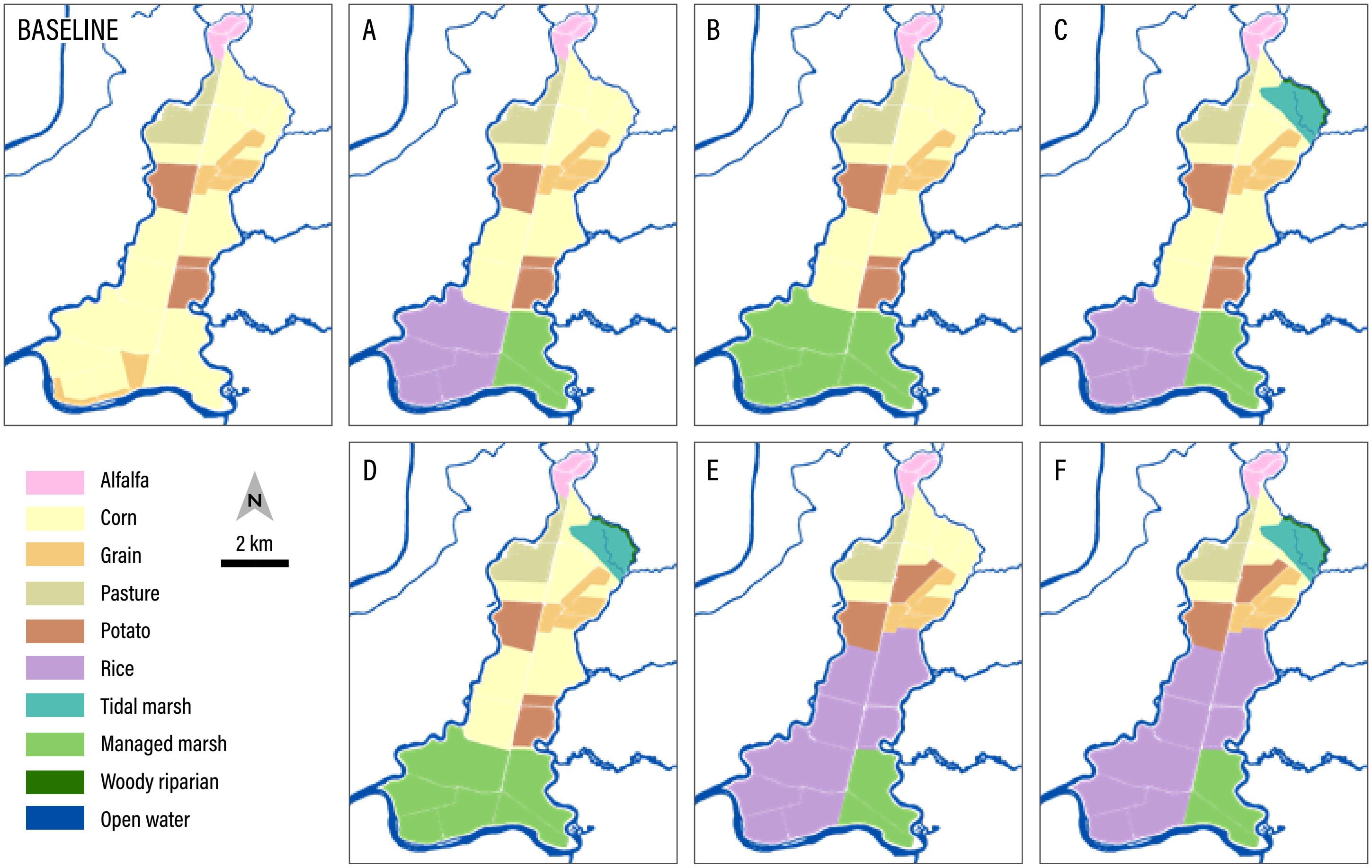


Figure 3. Staten Island baseline (2014 land use) and restoration and land use scenarios (A–F) evaluated for this pilot application to compare scenarios across multiple metrics related to ecosystem, land elevation, greenhouse gas emissions reductions, and economics.

Existing land elevations informed the placement of restored tidal marsh in the scenarios. The zone of minimal subsidence in the northern part of the island is most feasible for establishing tidal marsh in the near-term. Given the ecological benefits of tidal marshes as well as their relative resiliency to sea level rise, half of the scenarios (Scenarios C, D, and F) included over 200 ha of tidal marsh in the minimally subsided zone. This included a tidal channel, which was drawn to align with a historical channel (Figure 1a). Interior boundaries of the tidal marsh, where new levees would be required, were drawn based on locations of more inorganic soils (Figure 2b), which would be more stable for supporting levees.

Development of the scenarios was an iterative process, using on-the-ground knowledge for land use choices and spatial configurations as well as interim economic evaluations to guide acreages and crop mosaics. The relatively higher economic value of rice compared to marsh was the reason most scenarios included large areas of rice, even though marsh has greater subsidence reversal and GHG emissions benefits. Also, the total area of potatoes was kept relatively constant across the scenarios, given the relative profitability of the crop compared to other existing land use categories in the baseline. While other conventional crops (e.g., cotton, tomatoes) were also initially considered, the current mix of conventional crops was kept to minimize conversion costs and provide wildlife habitat benefits of current crops. Woody permanent crops, such as orchards and vineyards, were not considered given their low wetland ecosystem and carbon benefits.

Photo by California Department of Water Resources

SCENARIO EVALUATION APPROACH

The approach to assessing benefits and trade-offs from future land-use scenarios was to use science-based and transparent methods from previously vetted efforts. To evaluate the Staten Island scenarios for ecological benefits, land subsidence, GHG emissions, and economic impacts, a suite of metrics were assessed using several different tools and methods.

Ecosystem functions

To evaluate scenarios for their support of ecological functions, this analysis used the Landscape Scenario Planning Tool (LSPT, www.sfei.org/projects/landscape-scenario-planning-tool), which is an open-source tool funded by the Delta Stewardship Council and developed by the San Francisco Estuary Institute. It runs as a custom toolbox using ArcPython scripts within ArcGIS (ESRI). The LSPT was created to support landscape planning through the development, analysis, and comparison of different spatially-explicit land use scenarios in the Delta. It can be used to evaluate multiple objectives across a suite of metrics grouped into different modules relating to ecological functions, agriculture, and infrastructure. The metrics used to evaluate scenarios in the LSPT are based on prior research to understand past and present ecological functions and establish methods and metrics to evaluate them (SFEI-ASC, 2014). For this application, the primary ecological metrics used were those relating to marsh extent and configuration, wetland buffer, and hydrologic connectivity. More specifically, these metrics included: extent of marsh and riparian habitat types, total area of large marsh patches (> 100 ha, supportive of high marsh bird densities), distance to nearest large marsh patch, marsh shape (core to edge area ratio, where greater core area relates to habitat less affected by external disturbances including humans), woody riparian average patch size, percent of wetland buffer occupied by natural habitat types (e.g., woody riparian), marsh to open water ratio, percent of open water within 2 km of the nearest tidal marsh patch, and extent of hydrologically connected and regularly inundated area.

Given The Nature Conservancy's conservation focus on Sandhill Cranes for Staten Island management, a ranking approach was used outside of the LSPT to evaluate different land uses for their potential benefit to the wintering birds. Foraging and roosting benefits differ for different crops. Cranes prefer to roost in flooded agricultural fields and in marshes, typically at depths of around 10 cm (Ivey et al., 2016). Grain is considered to be best for foraging and rice for roosting. Ranking was based on land use and assumed management for foraging and roosting potential, given that how land is managed significantly affects habitat value (e.g., timing and depth of flooding). Ranking was applied as a simple score from 0 to 3 (0 = Not habitat, 1= Used, 2= Highly used but flooded only with additional management, 3 = Highly used and provides waste grains/additional calories). For example, pasture and alfalfa was assigned 0 for roosting habitat based on the assumption of no winter flooding. Also, while corn can provide roosting habitat, additional infrastructure is needed for typical management and so was ranked as a 2 instead of 3 like rice, which has the flood infrastructure in place. These crop suitability rankings for crane foraging and roosting were summarized at the island-scale using an area-weighted average.

Land elevation and greenhouse gas flux

Evaluation of potential land elevation change and GHG emissions relied upon the SUBCALC model, which was developed by HydroFocus, Inc., to simulate subsidence rates and is calibrated to quantify carbon emissions (Deverel and Leighton, 2010; Deverel et al., 2016). The approach to the evaluation here follows a prior application of SUBCALC to Staten Island, which focused on GHG emissions and economics of different land use scenarios (Deverel et al., 2017). The model applies enzyme kinetics for the oxidation of organic soils, where emissions are proportional to the carbon content of the unsaturated soil profile. In addition to the organic content of the soils, depth to groundwater, remaining peat thickness, and soil temperature are also inputs to the model. Estimates are based on an annual timestep, and the results are produced for each year of the simulation. SUBCALC incorporates a soil temperature model to reflect the predicted annual rise in soil temperature through the end of the century. The model has been updated over time and was recently calibrated based on recent eddy covariance and subsidence measurements from Staten Island as well as elsewhere in the Delta. For this analysis, SUBCALC was supplied with peat thickness and soil organic matter values reflective of the spatial variability of these inputs. This produced spatially dependent results in the form of a 90-ft resolution grid for the entirety of Staten Island. The organic matter component was based on the soil type distribution and peat thickness estimate developed by Deverel & Leighton (2010) and updated using the 2017 Delta LiDAR (CDWR, 2019). Areas mapped as organic soils but have little or no remaining peat were treated as mineral soils for the purposes of this analysis. The analysis uses subsidence values from SUBCALC in the agricultural areas with organic soils, a value of 0 for more inorganic-content soils and rice, and accretion of 3 cm yr^{-1} for marshes (Miller et al., 2008). For this evaluation, estimates for GHG emissions and reductions include CO_2 and methane (CH_4), and were based on estimates from research in the Delta (Hemes et al., 2019). Given that emissions change over time as organic matter oxidizes or accumulates, the net change in volume associated with subsidence or accretion and cumulative GHG emissions (t CO_2-e, metric tons of CO_2 and emissions from CH_4 and N_2O converted to the equivalent global warming potential of t CO_2-e using GWP factors of 28 and 265, respectively) were evaluated over a 50-yr time horizon (2014-2064).

Annual net revenue

To evaluate gross and net revenues associated with the land use scenarios, a modified version of the Open Delta Agricultural Production Model (OpenDAP, http://wsm.ucmerced.edu) was applied. OpenDAP is based on the Delta Agricultural Production Model (Medellín-Azuara et al., 2014), a positive mathematical programming-based (PMP, after Howitt, 1995) hydro-economic optimization model for agricultural production and water use for the Delta. PMP captures nonlinearities in crop production decisions and elicits economically optimal crop planting to adapt to economic and resource availability scenarios. The OpenDAP model characterizes agricultural land use in the Delta into over 130 individual sub regions including islands and inland areas. For this approach, a modified version was applied for the area of Staten Island.

The modified version of OpenDAP adds rice in the crop mix for selected scenarios and maintains the profit maximization objectives and constraints to estimate the effects of replacing existing crops and other land uses. Also, to quantify potential revenues from marsh, the modified version of OpenDAP used the economic benefit of carbon sequestration under current market values, adapted from Deverel et al. (2017). Carbon offset credits can be sold through compliance and voluntary markets, and prices for those credits vary ($7 per t CO_2 on the voluntary market and up to $30 per t CO_2 on the compliance market). A California base case of $16 was used for this analysis. For Staten Island, offsets for sale were estimated at 29.2t CO2 ha^{-1} yr^{-1} (11.8t CO_2 ac^{-1} yr^{-1}) based on the GHG emission reduction (marsh emissions subtracted from baseline emissions), with an adjustment for uncertainty and the need to contribute to a buffer pool in the event of project termination. The analysis used the annual cost of managed marsh from Deverel et al. (2017), at $101/ha ($41/ac).

After assigning scenarios rice and/or marsh areas, the remaining area was divided into other conventional crops through an interactive process using OpenDAP to maximize net revenue. Once the scenarios were set, gross and net revenues were calculated based on the area of different land covers and associated crop yield, prices, and costs derived from the OpenDAP model input economic database (Table 1). Costs considered include those related to land, supplies, labor, and water. Some costs were adjusted based on data specific to Staten Island. Most economic data were based on 2014 information. However, large fluctuations in corn prices made 2017 economics of production more suitable for corn in this analysis.

Table 1. Main land cover types on Staten Island with associated prices, yields, and total operating costs. Values were derived from the Open Delta Agricultural Production (OpenDAP) model, with some adjustments based on information specific to Staten Island.

Crop/Land cover	Price ($/ton)	Yield (ton/ha)	Total cost ($/ha)
Alfalfa	$254	18.04	$2,965
Corn	$151	12.65	$1,181
Grain	$235	8.11	$136
Pasture	$135	8.30	$1,065
Potato	$553	47.96	$16,975
Rice	$417	10.43	$1,940
Tidal marsh*	$16	29.16	$101
Managed marsh*	$16	29.16	$101

* CA base case emissions offset price and estimated Staten offset

Sandhill Cranes foraging on a Staten Island corn field. Photo by John Game

RESULTS

Multi-benefit summary

The goal of this multi-benefit scenario analysis pilot application was to be able to compare scenarios for a suite of benefits, without prioritizing any single benefit. Table 2 summarizes results for each category of metric, showing relative benefits and trade-offs of the six scenarios. (See the following sections and the Appendix for more detailed results.) This summary table illustrates that there are inherent trade-offs between scenarios and that no single scenario maximizes all benefits. Primary trade-offs relate to the presence or absence of tidal marsh in a scenario and the extent of rice included. Tidal marshes confer the greatest ecosystem benefits of any land use category, but with the economic trade-off of lost crop revenue; and rice halts subsidence and offers GHG benefits while maintaining crop revenues, but is generally less ecologically beneficial than marsh. Scenario F appears to accomplish a reasonable balance, improving conditions across all metric types, save for crane habitat support. While ecosystem metrics are slightly better overall for Scenario D, the economic benefits are lower than that of baseline conditions. And, while Scenario E is the best with regard to economic benefits, it does less well for other metric types than Scenarios C, D and F.

The landscape scenario analysis approach makes it possible to explore how one variable or benefit can be improved while minimizing negative impacts to others. For example, for Scenario F, rice was used as a way to reduce the area undergoing subsidence while also sustaining greater economic benefits than if the area were instead managed non-tidal marsh. Scenarios E and F also included shifting location of conventional crops for greater economic benefit. Namely, the area farmed for potatoes in the southern part of the island was converted to rice in these scenarios, and a new area to the north was converted from corn to potatoes to boost revenue.

The multi-benefit summary also demonstrates lost opportunities if the status quo is maintained. Many of these opportunities are more viable or beneficial in the near term. For example, introducing land uses now that keep peat soils wet has the greatest benefit for GHG emissions if done in the near-term. Also, opportunities for tidal marsh restoration may decline over time as subsidence progresses and sea level rises.

Table 2. Summary of scenario outcomes relative to baseline across categories of metrics. Blue represents improvement and yellow reduction. Checks indicate the greatest improvement.

Group	Metric Category	Scenario					
		A	B	C	D	E	F
Ecosystem	Marsh ecosystem support	🟦	🟦	🟦	🟦 ✓	🟦	🟦
	Aquatic ecosystem support	🟦	🟦	🟦 ✓	🟦 ✓	🟦	🟦 ✓
	Crane habitat	🟨	🟨	🟨	🟨		🟨
Inundation	Hydrologic connectivity			🟦 ✓	🟦 ✓		🟦 ✓
Land elevation	Wetted extent	🟦	🟦	🟦	🟦	🟦	🟦 ✓
	Net volume change 2014-2064	🟦	🟦	🟦	🟦 ✓	🟦	🟦
Carbon	GHG cumulative emissions 2014-2064	🟦	🟦	🟦	🟦 ✓	🟦	🟦
Economic	Annual net revenue	🟦	🟨	🟦	🟨	🟦 ✓	🟦

Ecosystem functions

Potential scenario benefits were evaluated for a suite of metrics related to ecosystem functions. All scenarios increased the extent of marshes (tidal and non-tidal), with the greatest expansion in Scenario D (~1,520 ha). In addition to overall extent, how marshes are configured in the landscape influences habitat complexity, species diversity, and overall wildlife abundance. Metrics of marsh patch size and average distance of patches to the nearest large patch also showed greatest improvements with Scenario D (Figure 4a, b). For this scenario, the area of large patches totaled approximately 1,510 ha, and the distance to nearest large patch was reduced to 1.3 km from 21 km under baseline conditions. Marsh core to edge area ratio was highest for Scenario B (5.2 : 1), as this scenario includes only a single large area of managed marsh (Figure 4c). Scenario D, which is the same as B wish added tidal marsh, is comparable (4.8 : 1). Scenarios C, D, and F increased woody riparian habitat (which was included adjacent to the tidal marsh in these scenarios). Area of natural marsh buffer was minimally impacted by the scenarios, with the percent buffer area as natural habitat types increasing to 3.5% for Scenario D over 1.4% under baseline conditions.

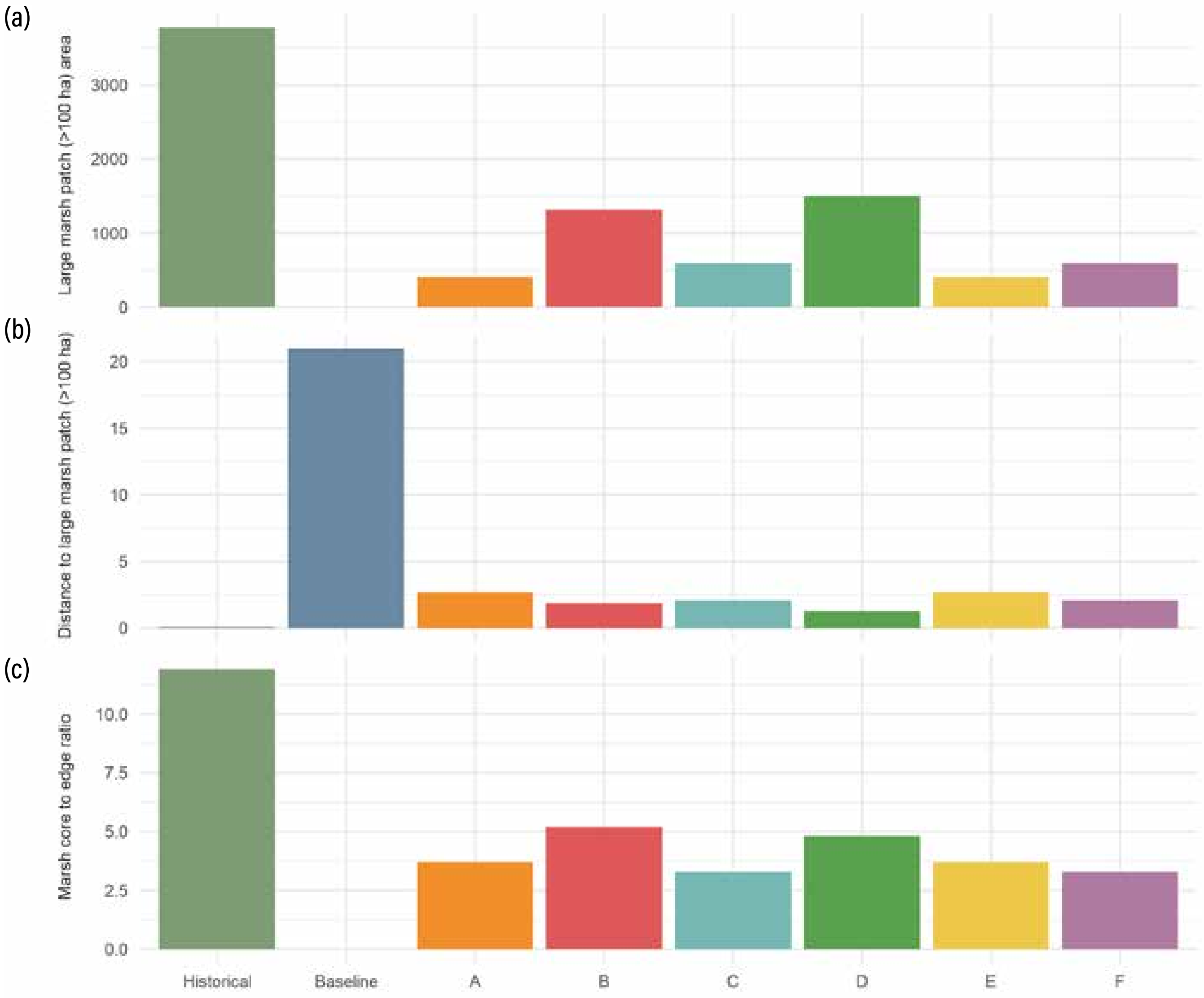


Figure 4. Comparison of Staten Island scenarios for, (a), total area of large marsh patches (> 100 ha), (b) nearest distance to a large marsh patch (> 100 ha), and (c), marsh total core area to total edge area ratio. No one scenario is best across all marsh metrics.

Improving hydrologic connectivity helps boost overall resilience potential for aquatic ecosystems over time by reestablishing fundamental natural physical and ecological processes that support exchange of abiotic matter and organisms between wetland and aquatic environments. These processes increase overall complexity and variability, and increase food web productivity. Connectivity benefits are greatest when areas of tidal marsh are added, but some can also be conferred by managed marsh if connections are established through artificial means. Considering both managed and tidal marsh, marsh to open water ratio increased to 3.1 : 1 from 0.04 : 1 under baseline conditions for Scenario D. Scenarios with the highest natural hydrologic connectivity are those that include tidal marsh, or Scenarios C, D, and F (Figure 5).

Results for Sandhill Crane habitat support (based on qualitative ranking of crop types) were mixed across the scenarios (Figure 6). Foraging suitability was lower for all scenarios given the loss in acreage of conventional crops, as grain crops in particular are considered to have high foraging benefits. In contrast, roosting suitability increased in scenarios with rice (Scenarios A, E, and F). Crane habitat benefits vary greatly depending on management (e.g., flooding timing, timing or characteristics of crop harvest), so the loss of suitable crops may be possible to offset in part by management practices.

Land elevation and greenhouse gas flux

Changes in land elevation across the scenarios, evaluated as a change in soil volume over the 50-year period (2014-2064), related to both land use and soil type (Figure 7). Scenarios B, C, D, E, and F resulted in net increases in volume, with Scenario D increasing the most (1.6 x 10^7 m^3). These are scenarios associated with the largest areas of marsh and rice on peat soils. This is exemplified in Figure 8, which shows the spatial distribution of annual subsidence and accretion rates for Scenario F. For Scenario A, which has substantial areas of peat soils remaining in conventional agriculture, there

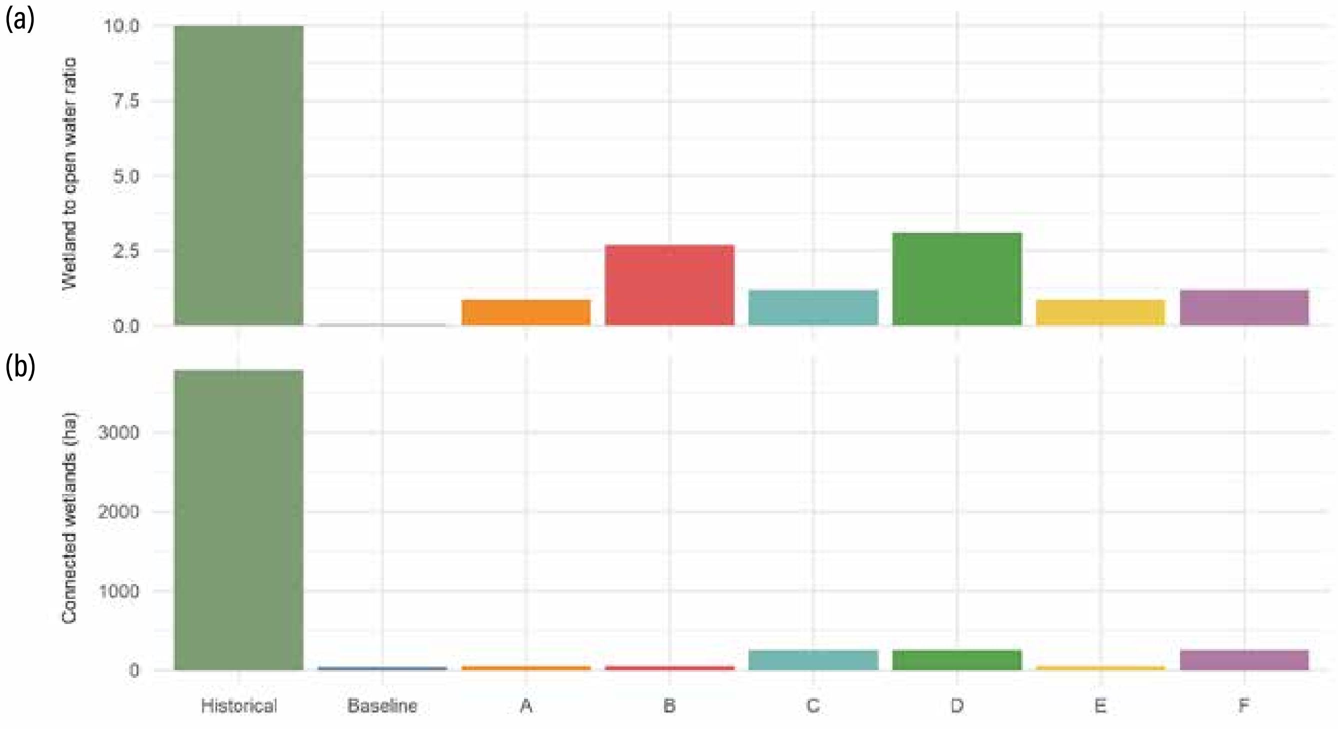


Figure 5. Comparison of Staten Island scenarios for metrics relating to hydrologic connectivity. Marsh (managed and tidal) to open water ratio is shown in (a) and area of hydrologically connected marsh is shown in (b).

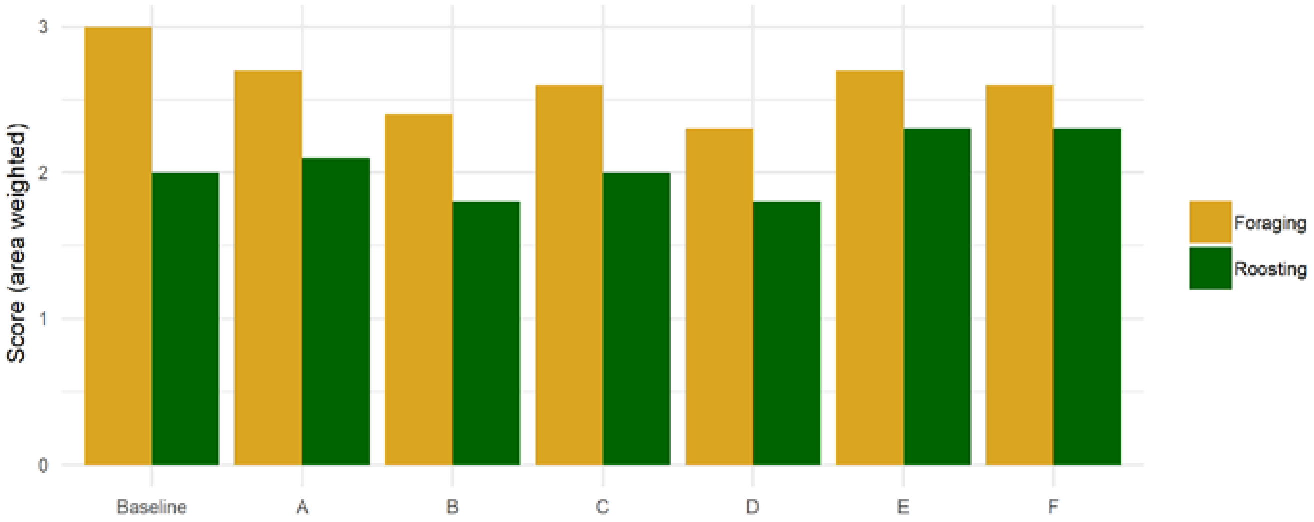


Figure 6. Using wintering Sandhill Crane foraging and roosting suitability scores (assigned from 0 to 3) for different crops and marsh types, area weighted scores are shown for each of the scenarios. While roosting potential is considered higher than baseline conditions for Scenarios E and F, the baseline scenario scores best for foraging potential.

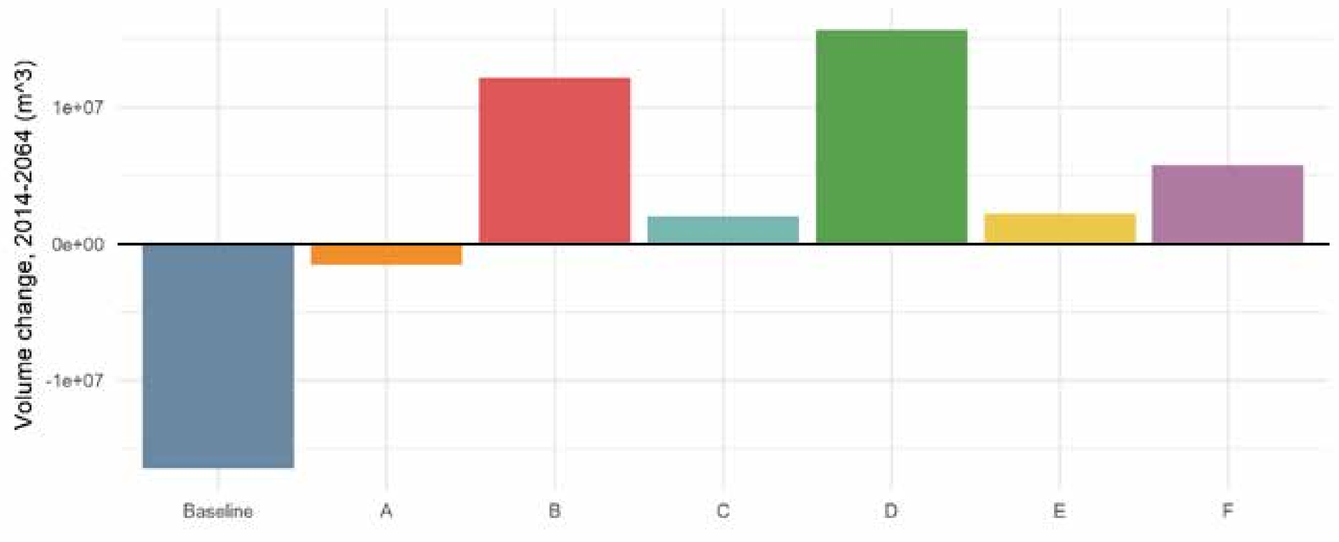


Figure 7. Cumulative 50-yr change in volume for the different scenarios based on variable subsidence and accretion estimated across Staten Island. All scenarios improve over baseline conditions, with Scenarios B, D, and F associated with estimates ofgreatest overall accretion over time.

was a net volume loss over time (1.5 x 10^6 m^3), though the losses were far less than those of baseline conditions (1.6 x 10^7 m^3).

GHG emissions reductions were associated with areas where marsh and rice covered peat soils as well as areas of more inorganic soils (Figure 9). Reductions were greatest for Scenario D (Figure 10). The cumulative emissions over the 50-yr period for this scenario were 1.9 x 10^6 t CO_2-e, compared to 3.8 x 10^6 t CO_2-e under baseline conditions (51% reduction). Scenarios B and F reductions were also high (48% and 40%, respectively). Even the worst performing scenario, Scenario A, reduced cumulative emissions by 31% (2.6 x 10^6 t CO_2-e). Although marsh and rice are net sources to the atmosphere of GHGs, marsh and rice emissions are far less than baseline GHG emissions from the oxidation of peat soils under drained agricultural management.

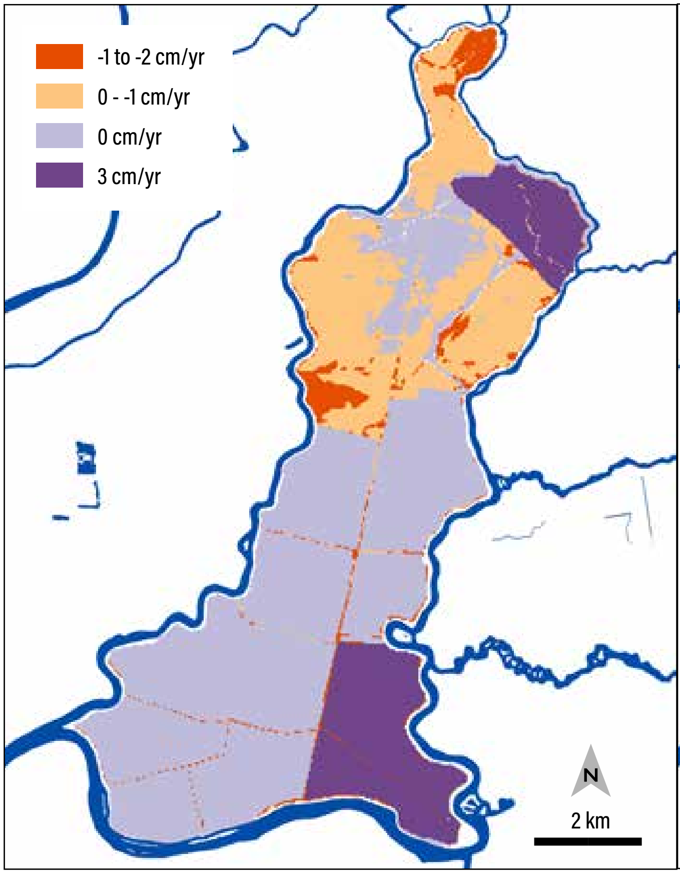


Figure 8. Distribution of annual rates of subsidence or accretion across Staten Island for Scenario F.

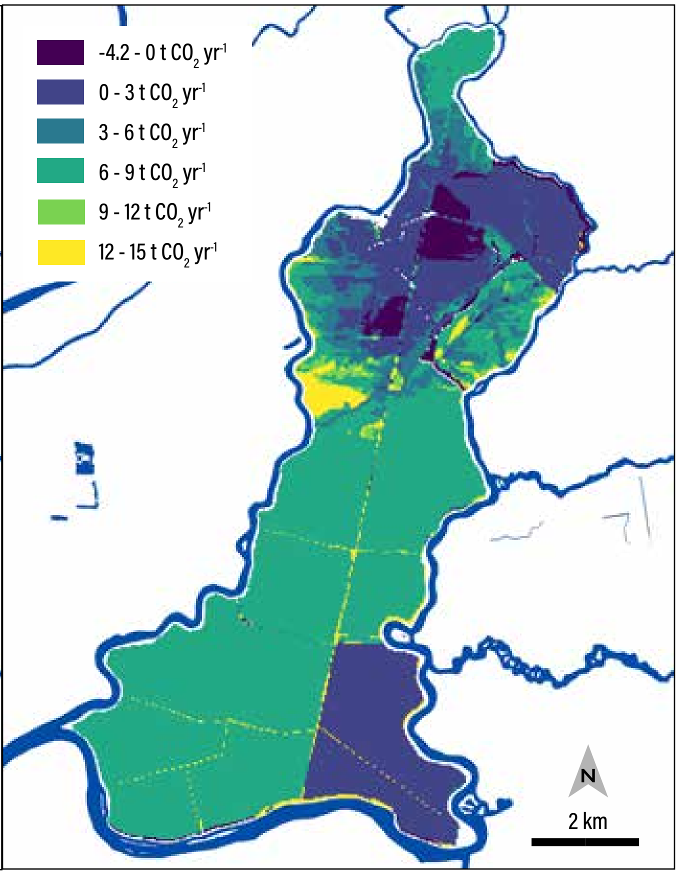


Figure 9. Distribution of average annual net GHG emissions across Staten Island for Scenario F.

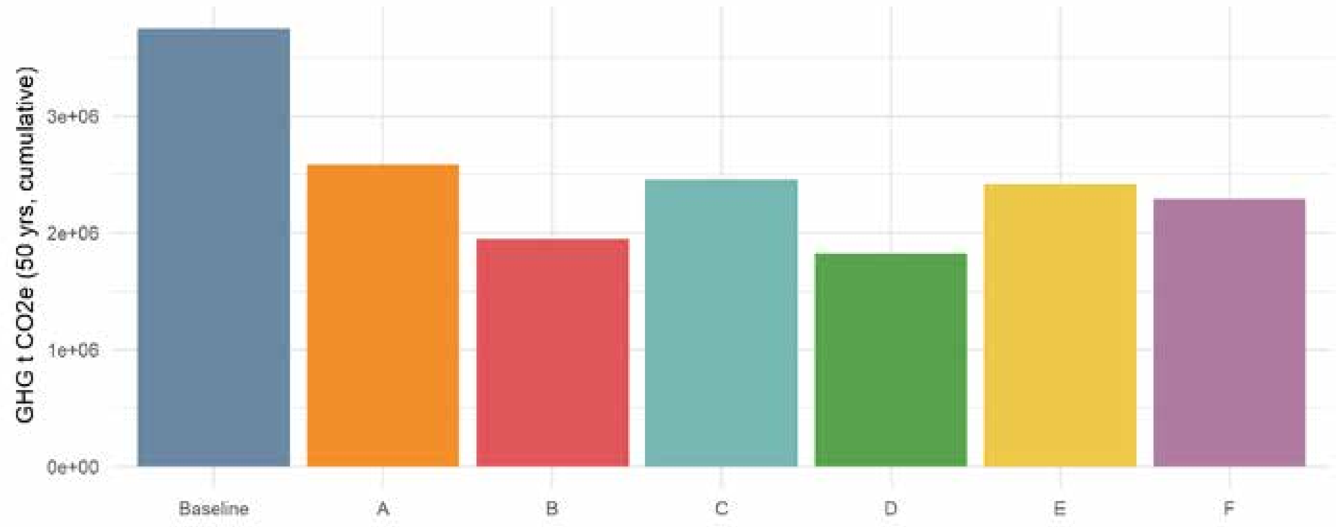


Figure 10. Cumulative GHG emissions across the scenarios, all of which substantially reduce emissions relative to the baseline, with scenarios B and D reducing the most.

Annual net revenue

Estimates of annual net revenue across the different scenarios varied between $5.0M and $7.9M, with $5.6M for the baseline scenario (Figure 11). Scenario E was associated with the highest net revenue, with Scenario F only slightly lower. All scenarios save for B and D (those that included marsh with no rice) were found to have higher estimated net revenue compared to the baseline (21-41%). Net revenue was dominated by potato and rice, given that these crops have relatively higher net returns. Across the scenarios, the carbon market revenue made up as much as 11% of the total net revenues. These results point to the importance of maintaining high-value crops for economic viability within a mosaic of land uses. More specifically, rice is a way to improve revenue, halt subsidence, and reduce GHG emissions, while also offsetting the lower profits from conversion of croplands to marsh. In this way, the economic benefits of rice can complement the large benefits of marsh for ecosystem function and greenhouse emissions. Note that this analysis does not include an ecosystem service monetary valuation, which would likely demonstrate fewer economic losses from establishing marsh.

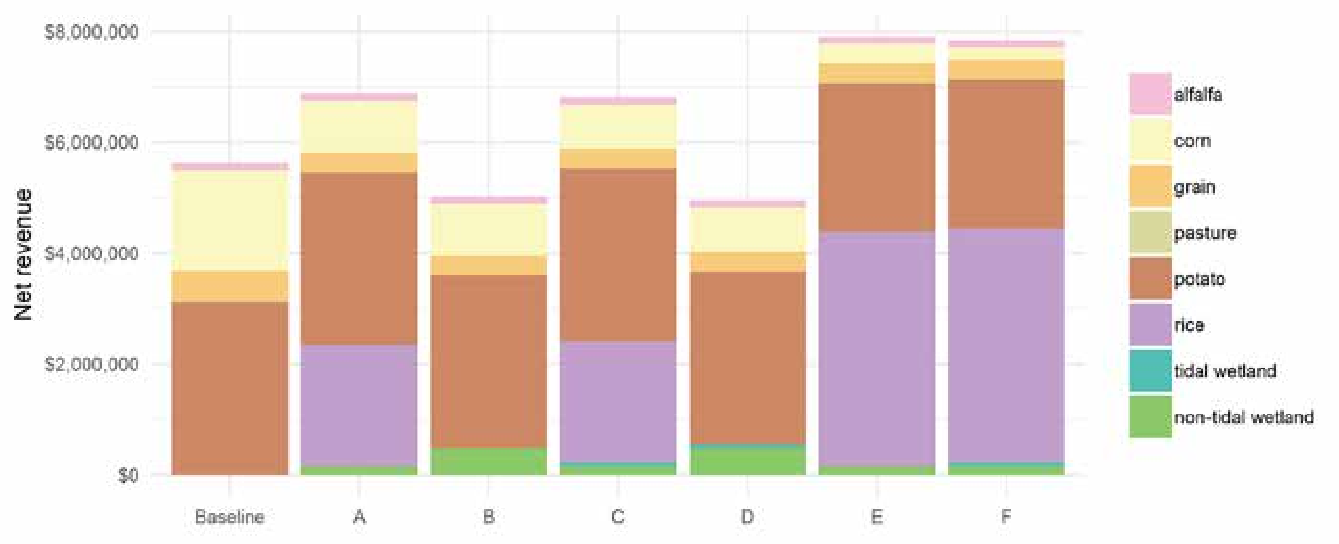


Figure 11. Annual net revenue estimates for the different scenarios. Scenarios with rice increase net revenues relative to the baseline.

Other cost and benefit considerations

This analysis takes a quantitative multi-benefit approach, evaluating metrics relating to several key types of benefits: ecosystem functions, land elevation, GHG emissions, and economics. In addition to these metrics, many other costs and benefits, both quantitative and qualitative, could be included in a multi-benefit analysis. A number of additional metrics were considered for this analysis, but ultimately were not included, either because information was lacking or scenarios would not have affected them greatly. These are discussed briefly here.

- The cost of maintaining levees to protect the Delta's subsided islands from flooding is significant. As land continues to subside and sea level rises, these costs increase. Additionally, the risk of more severe floods with climate change increases the risk of large expenditures for repairs. Baseline levee maintenance costs for Staten Island were estimated to be close to $800,000 annually. This is an average based on three years of costs (2017-2019) and does not include any specific projects or emergency repairs. With a total of about 41 km of levees surrounding

Staten Island, this equates to approximately $19,500/km of levee annually. These costs are also understood to be highly variable from year to year and from island to island in the Delta. Levee maintenance costs were not included as part of the scenario analysis in large part because the total length of levees was not found to change substantially across the scenarios (the length of levee decommissioned for the scenarios with tidal marsh was similar to the length of new interior levee that would be required for those scenarios). Aside from basic levee maintenance costs, the increased risk of need for expensive emergency levee repairs over time with continued land subsidence is also an important factor to consider, and scenarios that reduce the rate of subsidence could reduce levee maintenance costs relative to baseline conditions.

- Any land use conversions (from one crop to another or from cropland to restored marsh) are associated with monetary costs. For example, the cost associated with changing cropping from corn to potatoes was not included for Scenarios E and F. Also, restoration costs are generally high, including permitting, implementation, and the considerable cost associated with constructing new levees in a levee setback scenario. Capital costs (e.g., farm machinery) associated with the various land uses could also be included in addition to the primary operating costs that were evaluated for this analysis.
- Pumping costs are required both for irrigation of crops and to keep groundwater levels below the land surface. These costs for Staten Island are estimated around $160,000 annually. However, pumping costs depend highly on the crops being irrigated and specific farming practices, and also on environmental factors. (For example, costs are generally higher in wet years and in more subsided areas.)
- Other agricultural production costs that could be considered in future studies include water supply and agrochemical application. While water supply costs were included in this assessment, more information specific to a location or covering a broader scope of costs might enable more refined future analyses. In addition to the direct monetary costs of chemical and fertilizer applications, these activities also present associated environmental costs related to water quality.
- More detailed feasibility assessments would improve and refine any given scenario. This could include the need for hydrodynamic modeling to assess potential flood impacts, particularly for any scenario altering hydrologic connectivity. From a benefits perspective, such modeling could explore the potential for erosion and deposition processes, which could support land elevation recovery and riparian vegetation successional processes.
- Another area of potential economic and human health benefits is within the recreational sector. Depending on the scenario, these might be associated with a mix of hunting and ecotourism (lodging, birding, boating, etc.). Recreational benefits associated with marsh could help offset the comparatively lower profits these land uses offer in comparison to some agricultural activities.
- Lastly, numerous other metrics associated with ecosystem benefits could be considered, particularly as they relate to specific species or functions. For example, while Staten Island is known for and managed to support wintering Sandhill Cranes, cropping decisions and field inundation management is also guided by practices that would support other waterbirds. A more comprehensive assessment of waterbird benefits could be considered, particularly if scenarios were developed and evaluated based on management practices as well as land use differences.

NEXT STEPS

This pilot multi-benefit scenario analysis for Staten Island revealed a number of opportunities for future development that may guide a more comprehensive assessment for Staten Island or elsewhere. First, many of the quantitative metrics used in this study are associated with substantial uncertainty, whether related to modeling based on empirical data, inherent variability, or how scenarios are implemented. For more rigorous future assessments, a quantitative uncertainty analysis would allow for more robust conclusions. One area of high inherent uncertainty is crop prices. Even in the near term, year-to-year volatility in prices can substantially change the economic outlook of a scenario. For example, when corn prices are low, it makes conversion to rice more economically viable. This variability becomes even more important when looking several decades into the future. Also, with many outcomes highly dependent on specific management practices (e.g., inundation timing and depth, habitat enhancements such as hedgerows, chemical and fertilizer application rates), it may be useful to consider ways to more explicitly incorporate management into scenarios and metrics.

Developing approaches to more explicitly include temporal factors would make it possible to identify potential costs over time due to inaction in the present. This is essential information for incentivizing immediate action on appropriate land use activities that will keep future opportunities open and allow for continued adaptation as conditions change. This could include, for example, the evaluation of net present value (an expression of the current value of all future cash flows) as a way to explore projected benefits over time from investing in a project or action now. The ability to analyze scenarios that are phased over time will allow for more explicit development and evaluation of adaptation pathways (i.e., a series of land use modifications over time). For example, it may make more sense to prioritize restoring marshes now in some areas, given the opportunities offered and cumulative costs that will likely be avoided over time.

With regard to technical considerations for next steps, there is considerable opportunity to further integrate the modeling and analysis approach for multi-benefit scenario comparison. There are many methods, models, and tools that have been applied in the Delta to evaluate various benefits and costs associated with restoration and land use change. Multi-benefit assessments would be greatly facilitated if there were greater efforts toward connecting these approaches and potentially integrating models, where appropriate. Some of this work is currently underway. The Landscape Scenario Planning Tool (LSPT) has recently been expanded to include analyses of carbon stock changes and net greenhouse gas emissions reductions (funded by the Delta Stewardship Council and based on research funded by the California Department of Fish and Wildlife), based on the models and methods applied here and developed for the Delta by HydroFocus, Inc. (Deverel and Leighton, 2010; Deverel et al., 2016).

CONCLUSIONS

This pilot application for multi-benefit landscape-scale scenario analysis demonstrates the utility of the approach for envisioning a mosaic of land uses for future Delta landscapes that balance ecological support, subsidence mitigation, GHG emissions reductions, and economic viability. Results showed that a mosaic of land uses would be most appropriate for achieving the multiple objectives. This analysis illustrated the importance of rice for maintaining economic viability while also slowing or reversing land subsidence on peat soils. Further, evaluating these factors at the landscape scale showed how introducing managed and tidal marsh can provide ecosystem and carbon sequestration benefits, with the loss of agricultural revenue made up for in part by carbon market revenue and crops grown elsewhere on the island. All scenarios involved tradeoffs, with no one scenario maximizing all evaluated benefits. The application used the Landscape Scenario Planning Tool (www.sfei.org/projects/landscape-scenario-planning-tool), SUBCALC (Deverel and Leighton, 2010; Deverel et al., 2016), and OpenDAP (Medellín-Azuara et al., 2014), demonstrating how existing tools and methods can be leveraged in this type of analysis. Also, on-the-ground knowledge informed both the development of scenarios and model and tool parameterizations used to evauate scenarios, which made analysis outcomes more relevant to site-specific management decisions. For consideration in future studies, a number of uncertainties and additional costs and benefits were identified over the course this analysis. By envisioning and evaluating new practical approaches to the management of subsided lands in the Delta, this effort supports the continued development and integration of tools and approaches for establishing sustainable Delta futures that recover needed ecosystem functions while maintaining the Delta's economy, culture, and sense of place.

Photo by Kirk Klausmeyer, The Nature Conservancy

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APPENDIX

Detailed metric results comparing historical (where relevant), baseline (2014 conditions), and the six potential future land use scenarios for Staten Island. Blue highlights indicate which scenarios improved the most relative to baseline conditions.

Group	Metric	Subcategory	Historical	Baseline
Ecosystem	Habitat types: Extents (ha)	Open water	385	489
		Tidal marsh	3,782	18
		Managed marsh	0	25
		Woody riparian	78	15
		Agriculture (non-rice)	0	3,678
		Rice	0	0
		Urban/barren	0	19
	Marshes: patch size, total area (ha) of large patches (>100 ha)		3,782	0
	Marshes: nearest neighbor distance (km)		0.057	21
	Marshes: shape, core to edge area ratio		11.9 : 1	0.0 : 1
	Woody riparian patch size, average (ha)		77	1.9
	Wetland buffer extent & composition: Percent of total wetland buffer of natural terrestrial habitat types		100.00%	1.40%
	Aquatic ecosystem support: Marsh to open water ratio		10 : 1	0.037 : 1
	Aquatic ecosystem support: Connectivity of large marsh patches along fish migration corridors, Open water < 2 km from nearest large connected marsh patch		100.00%	3.80%
	Aquatic ecosystem support: Connected marsh (ha)		42,560	46
	Waterbird support: Crane foraging habitat (area-weighted rank)		NA	3
	Waterbird support: Crane roosting habitat (area-weighted rank)		NA	2
Inundation	Hydrologically connected area extent		NA	42
	Regularly inundated area and hydrologically connected extent		NA	14
Subsidence	Wetted extent		NA	23
	Net volume change (m^3), 2014-2064		NA	-1.64E+07
GHG emissions	GHG cumulative emissions, 2064 (t CO2e)		NA	3.75E+06
Economics	Annual gross revenue		NA	$14,648,812
	Annual net revenue		NA	$5,631,135
	Annual crop net revenue		NA	$5,631,135
	Annual carbon market net revenue		NA	$0

🟦	Largest improvement in metric relative to baseline conditions

Scenario A: South-end rice + marsh	Scenario B: South-end marsh	Scenario C: South-end rice + marsh; North-end tidal marsh	Scenario D. South-end marsh; North-end tidal marsh	Scenario E: South-end expanded rice + marsh	Scenario F. South-end expanded rice + marsh; North-end tidal marsh
489	489	492	492	489	492
18	18	205	205	18	205
431	1,341	429	1,339	431	429
15	15	30	30	15	30
2,363	2,363	2,160	2,160	1,514	1,311
910	0	910	0	1,759	1,759
19	19	18	18	19	18
409	1,320	596	1,507	409	596
2.7	1.9	2.1	1.3	2.7	2.1
3.7 : 1	5.2 : 1	3.3 : 1	4.8 : 1	3.7 : 1	3.3 : 1
1.9	1.9	4.3	4.3	1.9	4.3
1.50%	1.80%	2.80%	3.50%	1.50%	2.80%
0.87 : 1	2.7 : 1	1.2 : 1	3.1 : 1	0.87 : 1	1.2 : 1
8.60%	8.60%	22.20%	22.20%	8.60%	22.20%
54	54	256	256	54	256
2.7	2.4	2.6	2.3	2.7	2.6
2.1	1.8	2	1.8	2.3	2.3
42	42	229	229	42	229
14	14	201	201	14	201
1,338	1,338	1,526	1,526	2,187	2,375
-1.51E+06	1.21E+07	2.01E+06	1.57E+07	2.22E+06	5.74E+06
2.59E+06	1.95E+06	2.46E+06	1.82E+06	2.42E+06	2.29E+06
$16,280,410	$12,747,366	$16,008,764	$12,475,720	$17,233,776	$16,962,212
$6,886,705	$5,026,330	$6,817,820	$4,957,445	$7,912,805	$7,843,783
$6,738,609	$4,545,832	$6,601,293	$4,408,516	$7,764,709	$7,627, 256
$148,096	$480,498	$216,527	$548,929	$148,096	$216,528