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**Journal**

San Francisco Estuary and Watershed Science, 15(3)

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**Publication Date**

2017

**DOI**

10.15447/sfews.2017v15iss3art2

SEPTEMBER 2017

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

RESEARCH

# Implications for Greenhouse Gas Emission Reductions and Economics of a Changing Agricultural Mosaic in the Sacramento–San Joaquin Delta

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**Volume 15, Issue 3 | Article 2**
https://doi.org/10.15447/sfews.2017v15iss3art2

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## ABSTRACT

We quantified the greenhouse-gas (GHG) emission and economic implications of alternative crop and wetland mosaics on a Sacramento–San Joaquin Delta island: Staten Island. Using existing GHG fluxes measurements for the Delta and biogeochemical models, we estimated GHG emissions for a range of scenarios, including the status quo, modified groundwater management, and incorporating rice and managed wetlands. For current land uses, emissions were predicted to vary greatly (48,000 to 105,000 t $CO_2$-e $yr^{-1}$) with varying groundwater depth. GHG emissions were highest when water depth was 120 cm, the typical depth for a Delta island, and lowest if water table depth was shallowest (60 cm). In the alternate land-use scenarios, we simulated wetlands and rice cultivation in areas of highest organic-matter soils, greatest subsidence, and GHG emissions. For each scenario, we analyzed economic implications for the land-owner by determining profit changes relative to the status quo. We spatially assigned areas for rice and wetlands, and then allowed the Delta Agricultural Production (DAP) model to optimize the allocation of other crops to maximize profit. The scenario that included wetlands decreased profits 79% relative to the status quo but reduced GHG emissions by 43,000 t $CO_2$-e $yr^{-1}$ (57% reduction). When mixtures of rice and wetlands were introduced, farm profits decreased 16%, and the GHG emission reduction was 33,000 t $CO_2$-e $yr^{-1}$ (44% reduction). When rice was cultivated on 38% of the island, profit increased 12% and emissions were 22,000 t $CO_2$-e $yr^{-1}$ lower than baseline emissions (30% reduction). Conversion to a mosaic of wetlands and crops including rice could substantially reduce overall GHG emissions of cultivated lands in the Delta without greatly affecting profitability.

## KEY WORDS

greeenhouse-gas (GHG) emission, Sacramento–San Joaquin Delta, GHG emission reduction, wetland, rice, $CO_2$ fluxes, $CH_4$ fluxes, $N_2O$ fluxes, C offset, carbon cycle, agricultural economics

## INTRODUCTION

Many deltas worldwide are sinking because of reduced aggradation, compaction and soil loss caused by fluid withdrawal, soil drainage, and oxidation of organic matter (Syvitski et al. 2009). Deltas are also epicenters of urban and agricultural development (World Bank c2009). Changes have come at a significant cost. Many of the natural processes, and the species dependent on the natural processes and habitats, are in decline. Changes in landscape structure and process have also caused increasing flood risk, exacerbated by ongoing subsidence and sea level rise (Syvitski et al. 2009; Kirwan and Megonigal 2013). Cultivation of peat soils, also contributes significantly to greenhouse gas (GHG) emissions from these landscapes (e.g., Knox et al. 2015).

The Sacramento–San Joaquin Delta (Delta) was completely transformed after 1850 from the largest wetland system on the West Coast of the United States to a productive agricultural region, and is an important example of a sinking delta (Whipple et al. 2012). For more than 6,000 years the Delta consisted of over 300,000 hectares of intertidal freshwater marsh, tidal channels, and riparian floodplains, maintained by a dynamic equilibrium of sediment transport and deposition, and wetland soil formation (Atwater and Belknap 1980; Mount and Twiss 2005; Whipple et al. 2012). Reclamation of the Delta, primarily for farming, was completed by the 1930s, and the vast majority of drained tidal marsh was sequestered behind over 1,800 km of levees that protect nearly 200,000 hectares of farmland and serve as the hub of the state's water system (DSC 2013). Farming of organic soils resulted in substantial land subsidence, caused primarily by microbial oxidation of soil organic carbon (Deverel and Rojstaczer 1996; Deverel et al. 2016a), as well as compaction, burning, and wind erosion (Rojstaczer et al. 1991; Rojstaczer and Deverel 1995; Deverel and Leighton 2010).

Since the mid-19th century, over 2 billion cubic meters of soil disappeared, creating a large accommodation space below sea level, with elevations on Delta islands ranging from 1 to over 8 meters below sea level (Thompson 1957; Mount and Twiss 2005; Deverel et al. 2016a). Though subsidence has slowed as the organic-carbon content of Delta soils has declined and with improved land-management practices (e.g., ceasing of burning, and wind erosion prevention), subsidence is projected to continue, with additional land-surface elevation declines on many islands predicted to exceed 0.5 meter by 2050 if current land-management practices continue (Deverel and Leighton 2010; Deverel et al. 2016a).

Cultivation of the Delta organic soils caused a cycle: oxidation of organic matter leads to the need for deepening drainage ditches for maintenance of an aerated root zone, resulting in sustained oxidation and $CO_2$ emissions and further subsidence. A major consequence of subsidence is the increasing risk of levee failures that threaten the very farmland and water-conveyance systems the levees are maintained to protect (Mount and Twiss 2005; Florscheim and Dettinger 2007; Lund et al. 2010; Suddeth 2010). Since 1930, there have been approximately 100 levee breaches (163 in the last 100 years). The cumulative probability of levee failure on any island in the Delta was estimated to be 80% by 2050, with an over 90% probability of 10 islands failing simultaneously within the next 50 years (URS Corp & J. R. Benjamin Associates 2009; Lund et al. 2010). Cultivation of peat soils in the Delta contributes disproportionately to GHG emissions in California relative to agriculture on low organic-matter soils (Hatala et al. 2012; Li et al. 2014; Knox et al. 2015). The global warming potential of lands in this Delta is higher than other regions with highly organic soils (Teh et al. 2011).

Recognizing the need for significant land-use change in the Delta, the State of California, federal agencies, and others have called for development and implementation of proposals to reduce subsidence and levee risk, while natural processes and ecosystems are also restored to allow recovery of imperiled species. The current governing legislation and vision for reconciling ecosystem and human needs in the Delta has established improving water supply reliability and ecosystem restoration as co-equal goals that should be accomplished while the unique cultural values of the Delta, including agriculture, are preserved (DSC 2013). Also, legislation passed in 2016 (SB 32, Pavley) requires California to meet one of the world's most ambitious goals for reducing GHG emissions, bringing emissions in California to less than 40% of 1990 levels by 2030.

Additionally, the California Air Resources Board has set administrative targets to reduce emissions to less than 80% of 1990 levels by 2050 (*http://www.arb.ca.gov/cc/ab32/ab32.htm*). One state-proposed mechanism for achieving these targets is the Cap-and-Trade Program, which includes an overall limit on GHG emissions from capped sectors and carbon offset purchases for compliance with the total GHG emissions limits. Offsets are typically achieved through financial support of projects that reduce GHG emissions based on established protocols. The American Carbon Registry recently approved a protocol for restoration of California Deltaic and coastal wetlands and rice (Deverel et al. 2017).

Significant Delta land-use changes will result in GHG emissions reductions, subsidence mitigation, and ecosystem reconciliation. These include rice cultivation and managed wetlands (Miller et al. 2008; Hatala et al. 2012; Deverel et al. 2016a). Flooded land uses, such as rice and wetlands, will play a critical role in meeting ecosystem restoration and conservation goals for the Delta and California. For example, flooded agriculture now represents vital habitat for migratory waterbirds along the Pacific Flyway (Stralberg et al. 2010); over 7 million waterfowl, shorebirds, and other waterbirds annually rely on flooded fields in the Central Valley, including the Delta.

The GHG and economic implications and trade-offs of alternative land use mosaics that could reduce emissions, mitigate subsidence, and provide critical habitat for terrestrial species have heretofore not been explored. In this study, we quantified the GHG emissions and economic implications of alternative crop and wetland mosaics on the 3,700-ha Staten Island in the central Delta (Figure 1), where organic or highly organic mineral soils predominate.

Our understanding of GHG dynamics in the Delta has evolved since the early 1990s. Early work demonstrated the relation of GHG emissions to subsidence, and the benefit of permanently flooded wetlands in reducing carbon losses and mitigating subsidence (Deverel and Rojstaczer 1996; Deverel et al. 1998; Miller et al. 2000, 2008). Millennial undisturbed carbon sequestration rates in the Delta were determined by Drexler (2009).

Several studies focused on wetlands CH4 emissions and emissions reduction (Anderson et al. 2016; Knox et al. 2015), and on wetland $CH_4$ production and transport (Poindexer et al. 2016). GHG fluxes have been quantified for Delta crops, including corn (Pellerin et al. 2013; Knox et al. 2015; Yang and Silver 2016), pasture (Sonnentag et al. 2011; Teh et al. 2011; Hatala et al. 2012), and rice (Hatala et al. 2012; Matthes et al. 2015; Knox et al. 2016; Ye et al. 2016; Morris et al. 2017). Monitoring of ecosystem-scale $CO_2$ and $CH_4$ fluxes using the eddy covariance technique (Baldocchi 2014) demonstrated that GHG fluxes in wetlands vary among years and age (Knox et al. 2015; Anderson et al. 2016), and are affected by water- and land-management practices (Miller 2011; Oikawa et al. 2017), and vegetation cover (McNicol et al. 2017). Recent research focused on modelling GHG dynamics of restored wetlands in the Delta (Oikawa et al. 2017) and the use of remote sensing (Mathes et al. 2017).

Using existing empirical data for GHG dynamics for the Delta, we herein report estimates of GHG budgets for a range of scenarios for Staten Island, from the status quo to incorporating significant proportions of rice and managed wetlands. For each scenario, we analyzed economic implications for the land-owner by determining profits, losses, or gains relative to the status quo using an economic-optimization model.

Converting traditional crops to managed wetlands with no quantifiable market value can be a very costly decision for land-owners. Wetlands are not traditionally considered to be economically beneficial, even though they provide numerous non-market values such as ecosystem services that include recreation, nutrient regulation and supply, soil and sediment regulation, flood and natural hazard protection, cultural values, water-quality benefits, and improved habitat and biodiversity (U.S. EPA 2008). To a lesser degree, this is also true for some traditional crops such as rice, because they provide values such as breeding and feeding habitat for waterfowl, which are not fully captured in market prices of the harvested grain. To correct these market “failures,” policy mechanisms can internalize these non-market values, providing financial incentives for growers. Therefore, we included in our simulations a GHG offset market for wetlands, and thus provided a policy-relevant example of the trade-offs associated with various Delta land uses.

## METHODS

Staten Island represents the typical range of soils and crops for the central Delta. Soils vary from highly organic or true histosols (Rindge Muck) in the southern and central parts of the island to mostly

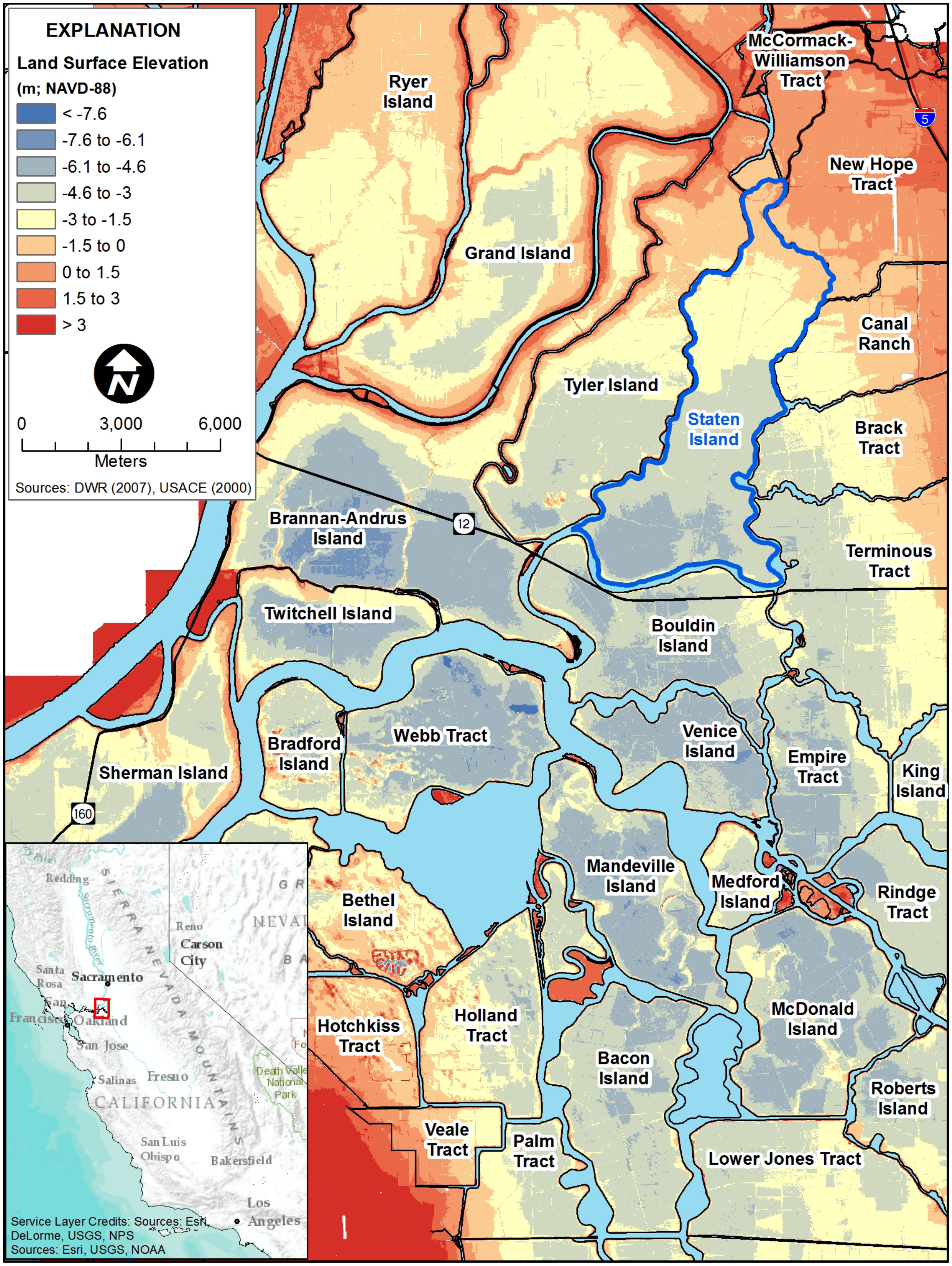

**Figure 1** Location of the Sacramento–San Joaquin Delta and Staten Island and land surface elevations

highly organic mineral soils in the northern part of the island, where there is also an area of true organic soil or histosol (Figure 2). The thickness of the organic soils generally varies from less than 1 m in the north to over 3 m in the south, and is greatest in the southwest part of the island where it approaches 6 m (HydroFocus, Inc. 2012).

Staten Island was drained and leveed for agriculture in the 1860s and has experienced as much as 4.8 m of subsidence in the southern part of the island since the early 1900s. In the northern and central parts of the island, subsidence ranges from 0 to over 4.3 m. Greater subsidence is associated with areas of relatively higher soil organic matter content (Figure 2).

Staten Island agricultural management practices minimal tillage; crop residue typically remains on the soil after harvest. Groundwater depths range from 30 cm in the pasture to 90 cm on the rest of the island, shallower relative to most central Delta islands where groundwater levels are typically about 120 cm below land surface. In 2014, most of Staten was planted to corn (2,610 ha), which had been a predominant crop for over 10 years (HydroFocus, Inc. 2012). Alfalfa (109 ha), pasture (272 ha), potatoes (364 ha), and triticale (374 ha) were also grown (Figure 3).

## Staten Island Scenarios

To assess the GHG emissions and economic implications of the effects of alternative land use, management practices, and depth to groundwater, we evaluated six scenarios shown in Table 1. Figures 3–6 illustrate the scenario land uses. We attempted to answer questions about GHG emissions and island profitability relative to business as usual and Staten Island baseline conditions. We defined a baseline scenario as the 2014 crop mix and current depth to water table (Figure 3, Table 1). Alternative scenarios were developed to investigate the effects of different water- and land-management practices, and restoring flooded ecosystems on GHG emissions (Table 1). For Scenarios 1 and 2, we investigated the effects of depth to groundwater on GHG emissions relative to baseline or business as usual. In Scenarios 3, 4, and 5, we assessed the GHG emission effects of including varying areas of rice and managed wetlands. We based wetlands and rice assessments on soil type and water-management considerations. To maximize profits, an economic optimization model allocated the remaining areas to traditional crops (potatoes, corn, alfalfa, triticale, and pasture). For Scenarios 3–5, wetland and rice were simulated on the most subsided part with the highest percent organic matter soil, and we assumed the depth to groundwater for crops other than rice was 90 cm, as in baseline conditions. For all scenarios (1–5) depth to groundwater for pasture was 30 cm (HydroFocus, Inc. 2012).

GHG emissions included (1) $CO_2$ fluxes, (2) $CH_4$ produced in flooded conditions and in pasture, and (3) $N_2O$ emissions, which were derived from soil oxidation and fertilizer applied to crops. Though $CO_2$ is the most abundant GHG in the atmosphere, both $N_2O$ and $CH_4$ are more potent, i.e., have a greater global warming potential. All GHG emissions were expressed in tons of $CO_2$ equivalents (t $CO_2$-e) with $N_2O$ and $CH_4$ having 265 and 28 times the global warming potential of $CO_2$ on a 100-year timescale, respectively (Myhre et al. 2013). We estimated GHG emissions independently for five zones that corresponded to varying elevation and historic subsidence rates and soil organic matter content as described in HydroFocus, Inc. (2012) (Figure 7).

For scenarios that included wetlands and rice, the net GHG flux was calculated as the net sum of $CO_2$ removed from the atmosphere minus $CH_4$ emissions by wetlands and rice and minus additional $N_2O$ emissions from rice, expressed as $CO_2$-e. Negative flux values denote net removal of GHGs from the atmosphere; positive flux values denote net GHG emissions. To estimate the GHG emissions reduction of each scenario for Staten Island, we subtracted $CO_2$, $N_2O$, and $CH_4$ fluxes for the scenario from baseline GHG emissions.

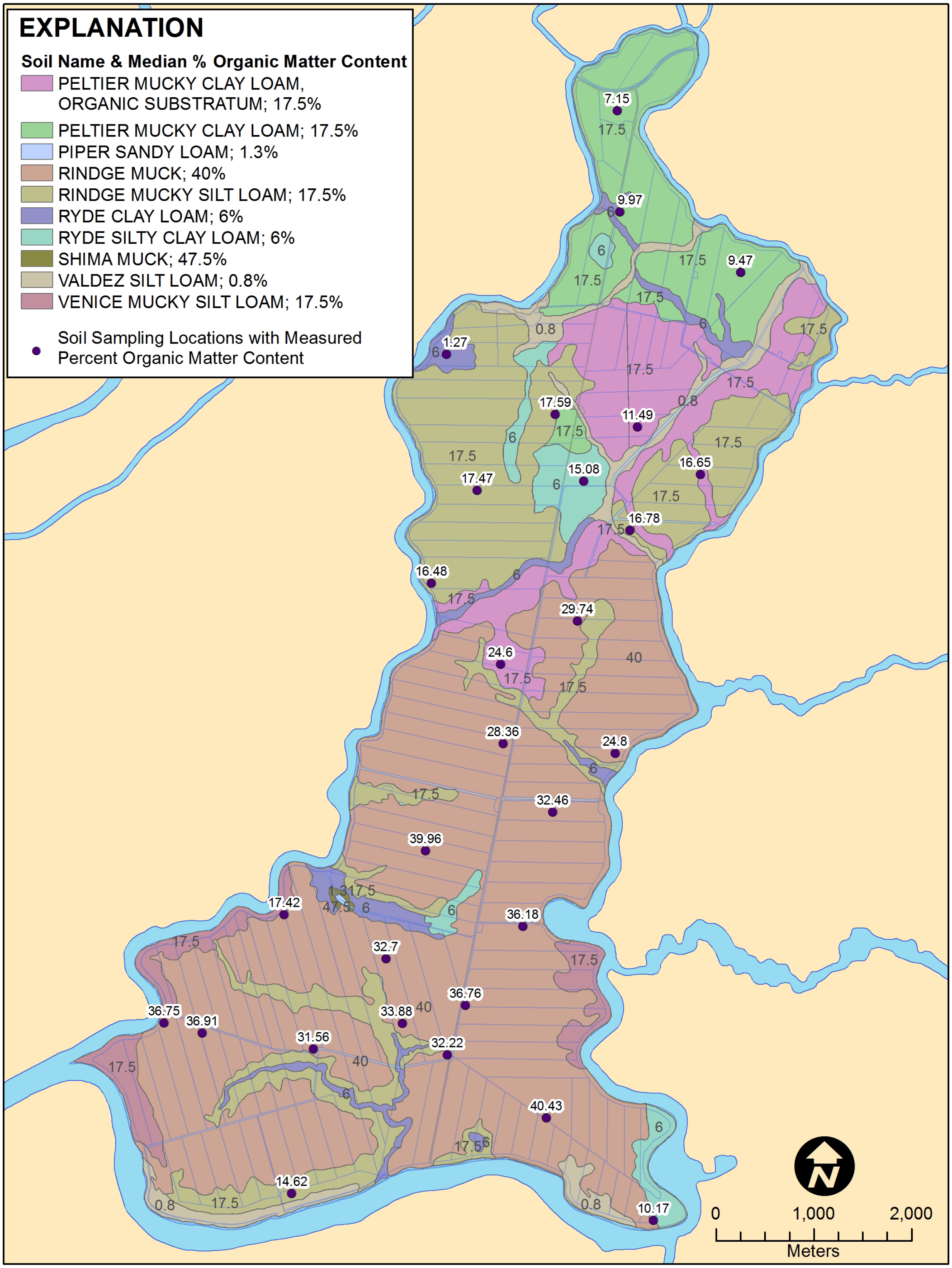

**Figure 2** Distribution of Staten Island soils and percent organic matter in samples collected in 2011. Percent organic matter values for soil series listed in the explanation represent the mid-point of values presented in McElhinney (1992)

**Table 1** Scenarios for different GHG emissions estimates for Staten Island (3,730 ha)

| Scenario | Groundwater depth for crops (cm) | Crop | Rice area (ha) | Wetland area (ha) | GHG Net flux, 2014 (t $CO_2$-e $yr^{-1}$) | GHG Net flux, 2064 (t $CO_2$-e $yr^{-1}$) |
|---|---|---|---|---|---|---|
| Baseline | 90 | 2014 mix of corn, potatoes, triticale, pasture, alfalfa.<br>Minimal tillage | 0 | 0 | 79,140<br>(±14,350) | 71,890<br>(±13,030) |
| 1 | 120 | Typical central Delta Island groundwater depth with Staten 2014 crop mix of corn, potatoes, triticale, pasture, alfalfa.<br>Conventional tillage | 0 | 0 | 105,100<br>(±19,130) | 95,390<br>(±17,360) |
| 2 | 60 | 2014 mix of corn, potatoes, triticale, pasture, alfalfa.<br>Minimal tillage<br>Shallow water table | 0 | 0 | 53,180<br>(± 9,460) | 48,390<br>(±8,610) |
| 3 | 90 | Wetlands in highest organic soils.<br>Minimal tillage | 0 | 1,787<br>(48% of the island) | 33,520<br>(±8,500) | 31,500<br>(±7,990) |
| 4 | 90 | Rice and wetlands in highest organic soils.<br>Minimal tillage | 1,189<br>(32% of the island) | 598<br>(16% of the island) | 43,480<br>(±5,900) | 41,450<br>(±5,620) |
| 5 | 90 | Rice in highest organic soils.<br>Minimal tillage | 1,433<br>(38% of the island) | 0 | 55,230<br>(±7,180) | 52,100<br>(±6,760) |

## Estimation of Staten Island Greenhouse Gas Emissions

### *Carbon Dioxide and Methane*

To estimate $CO_2$ emissions for baseline and scenario conditions, we used the SUBCALC model. The SUBCALC model was originally developed using historic land-surface elevation data collected in the central Delta to quantify and simulate subsidence rates and causes (Deverel and Leighton 2010). The model was updated and recalibrated using recent data for $CO_2$ emissions (Deverel et al. 2016a). SUBCALC simulates aerobic microbial oxidation of organic matter, consolidation, wind erosion, and burning. SUBCALC simulates microbial oxidation using Michaelis–Menten enzyme kinetics in which the rate of soil organic-matter oxidation is limited by soil organic carbon content. For each annual time-step, the different contributions to subsidence are estimated based on the newly calculated mass of organic matter and bulk densities. Primary inputs for SUBCALC are depth to groundwater, soil temperature, and soil organic matter content. The depth of the organic soil where oxidation is simulated to occur is determined by the depth to groundwater, and the oxidation rate is governed by depth-to-groundwater/carbon loss–subsidence relations. Additional information about the model and inputs and validation can be found in Appendix B in Deverel and Leighton (2010). Deverel et al. (2016a) reported the most recent model update and validation.

On Staten Island, soil organic matter content generally increases from north to south, concomitant with depth of subsidence. We estimated soil $CO_2$ emissions independently for each of the five zones of Staten Island (Figure 7). The SUBCALC model was applied independently in each of the five zones and summed to estimate total $CO_2$ emissions for Staten for each of the different scenarios. For SUBCALC inputs, we utilized an area-based weighted average for soil organic matter content from samples collected in 2011 for each zone (HydroFocus, Inc. 2012) and by soil organic matter estimates in McElhinney (1992). We validated the SUBCALC model for Zone 3 by comparing modeled $CO_2$ emissions estimates with USGS $CO_2$ emissions data collected in 2012 and 2013 (Pellerin et al. 2013). Using eddy covariance, Pellerin et al. (2013) measured 21.3 t $CO_2$-e $ha^{-1} yr^{-1}$ for corn. Using SUBCALC, we estimated 21.1 t $CO_2$-e $ha^{-1} yr^{-1}$.

In the pasture, $CH_4$ emissions from animal enteric fermentation were added to GHG emissions

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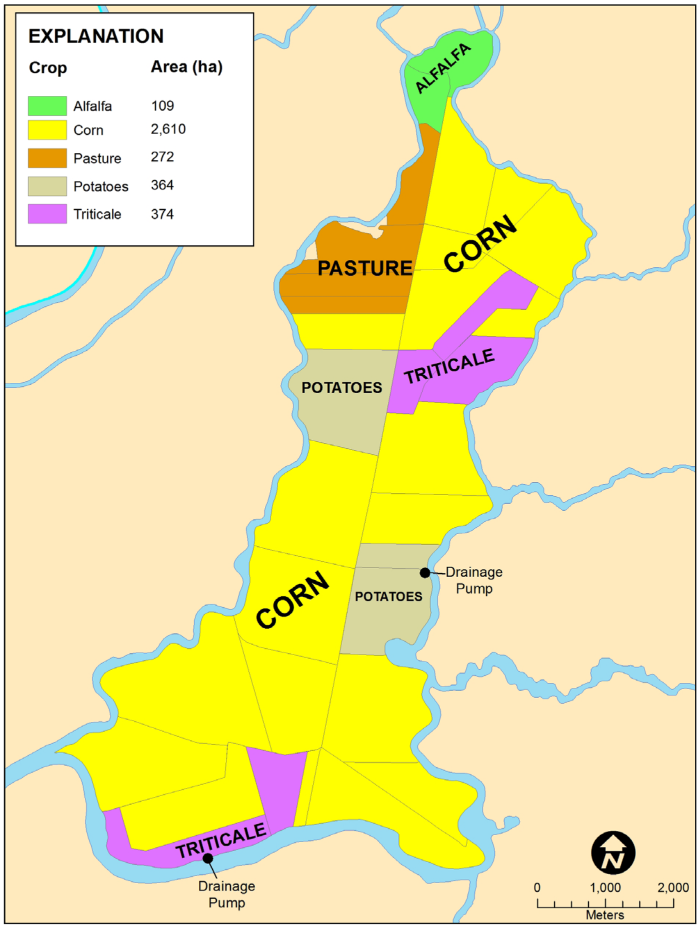


**Figure 3** Crops grown on Staten Island in 2014 used for baseline and management scenarios

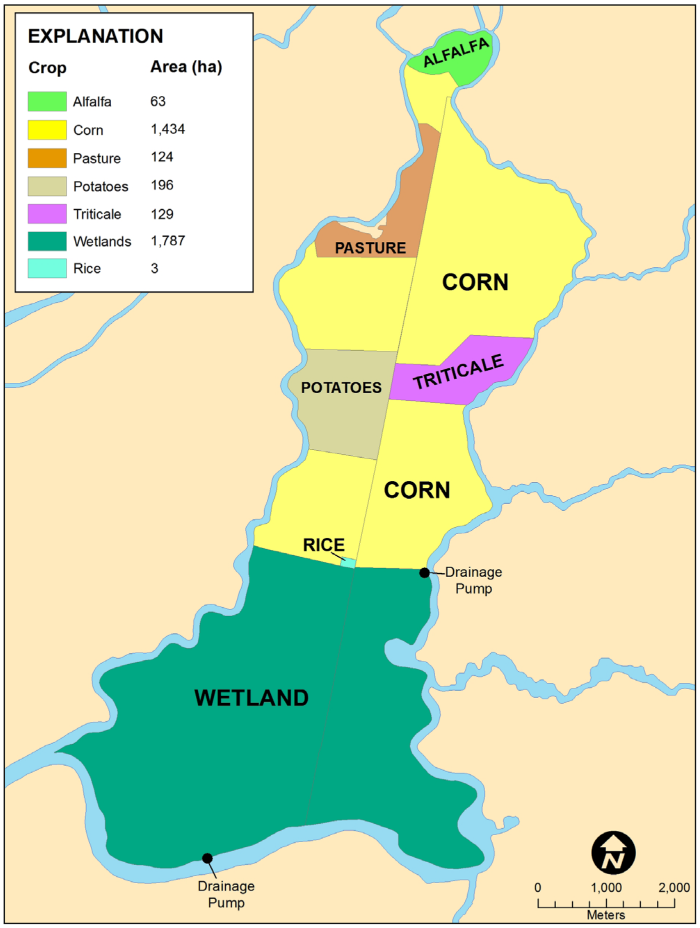


**Figure 4** Distribution of crops and wetlands for Scenario 3

resulting from soil oxidation obtained from the SUBCALC model. We used the emission rate of 80 kg $CH_4$ $ha^{-1} yr^{-1}$ per head of cattle available from the Environmental Protection Agency (*http://www.epa.gov/rlep/faq.html*) and the cattle density of approximately 2 head of cattle $ha^{-1}$ provided by the Staten Island farm manager.

## Nitrous Oxide

Nitrous oxide emissions result from fertilizer and oxidation of organic soils. To estimate baseline Staten Island $N_2O$ emissions from fertilizer applications, we used the DeNitrification–DeComposition (DNDC) model (Li et al. 2014; University of New Hampshire 2012). The DNDC is a process-based model that simulates carbon and nitrogen biogeochemistry in agricultural systems based on climate, soil, crop, vegetation, and management practices. The model consists of two components: (1) calculation of soil temperature, moisture, pH, redox potential, and substrate concentration profiles; and (2) calculation of nitrogen emissions using nitrification, denitrification, and fermentation sub-models.

To simulate the nitrous oxide emissions by crops, the DNDC model requires site-specific inputs for climate data, fertilizer applications, nitrogen deposition in precipitation, soil texture, and crop practices. We obtained daily climate data that contained minimum and maximum temperature, precipitation, wind speed, and relative humidity from the California Irrigation Management Information System (CIMIS) station on Twitchell Island for 2012 and 2013 (*http://www.cimis.water.ca.gov/Default.aspx*). We obtained data for nitrogen concentration in rainfall from the Davis Station (Site 88), using ammonium and nitrous

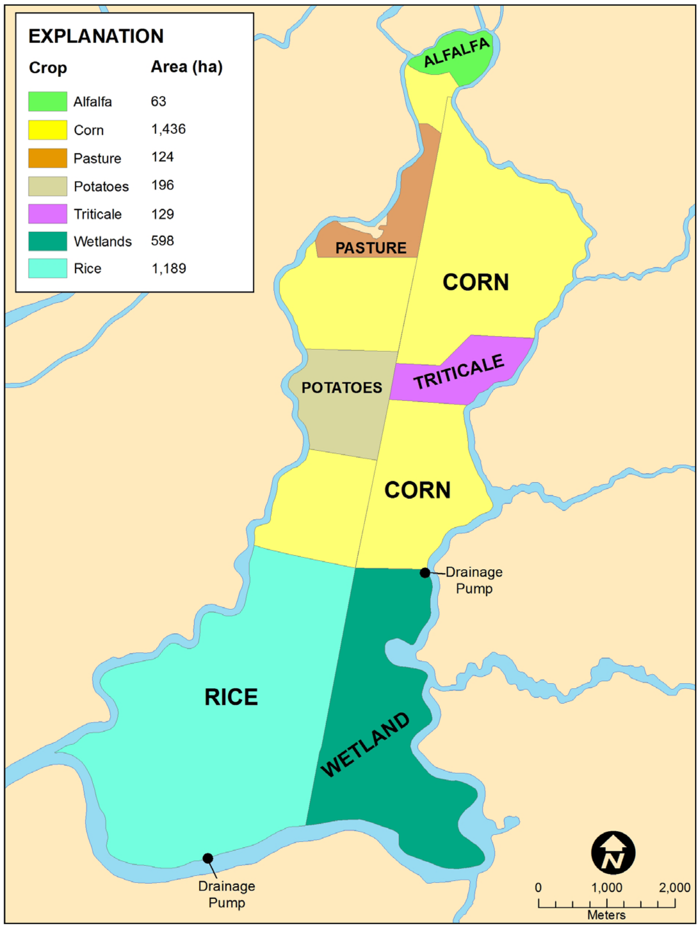


**Figure 5** Distribution of crops and wetlands for Scenario 4

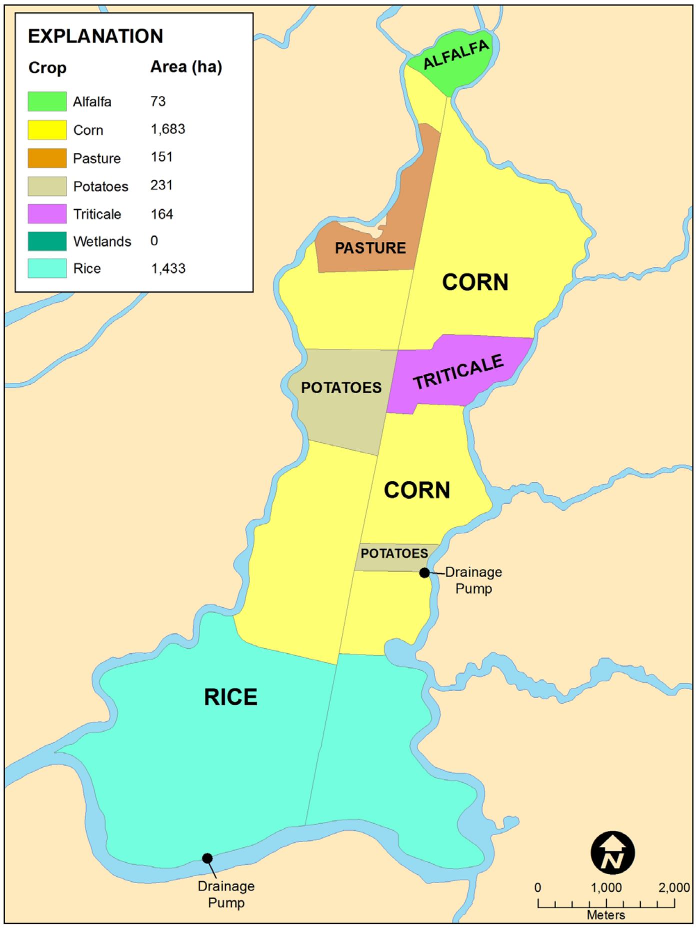
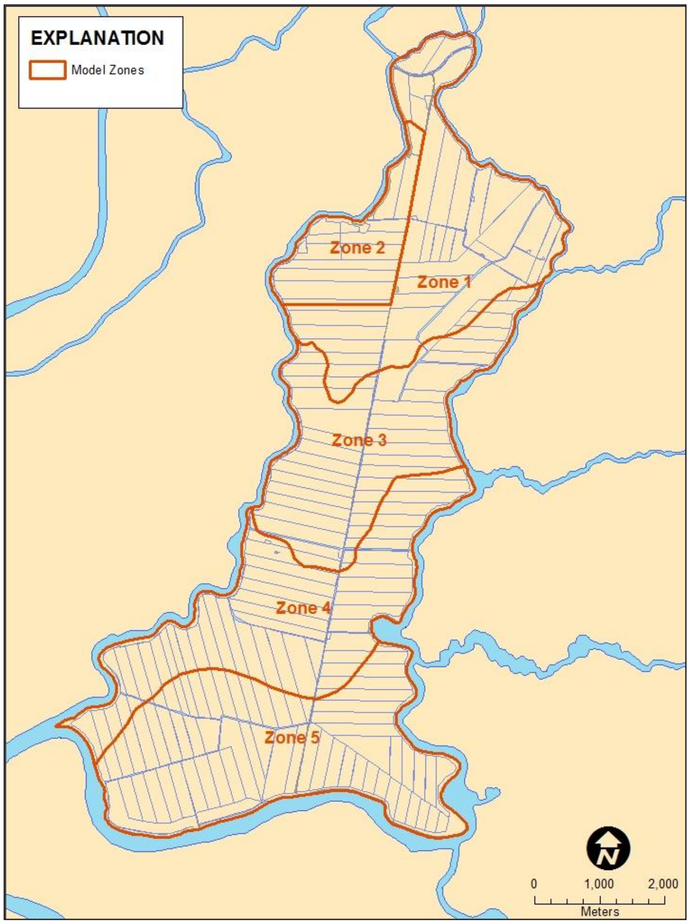


**Figure 6** Distribution of crops for Scenario 5

oxide concentrations determined in rainfall in 2013 (*http://nadp.isws.illinois.edu/data/sites/siteDetails.aspx?net=NTN&id=CA88*). We estimated a daily average rainfall value of 0.72 mg nitrogen per liter.

The DNDC model contains pre-specified soil textures. For Staten Island, we used cultivated/drained peat soil. Soil bulk density, pH, organic-matter content, carbon-to-nitrogen ratio, and porosity were obtained from the USGS data set (Pellerin et al. 2013) and HydroFocus Inc. (2012). To simulate $N_2O$ emissions, we adjusted the organic-matter decomposition constants in DNDC to match the USGS emission data for carbon dioxide. We set soil moisture parameters (field capacity and wilting point) to the model default values. Specific values for crop management, including planting and harvest dates, irrigation volumes and dates, fertilization amounts, and crop yield were provided by the Staten Island farm manager.

To quantify $N_2O$ emissions from soil organic matter decomposition, we used simultaneously measured $N_2O$ and $CO_2$ emissions from corn and pasture on nearby Twitchell and Sherman islands (Teh et al. 2011; Morris 2014; Morris et al. 2017; Yang et al. 2016). From measured total $N_2O$ emissions in corn, we subtracted the DNDC-estimated annual $N_2O$ flux from fertilizer application of 0.3 kg N $ha^{-1} yr^{-1}$. We assumed that the remaining emissions were from the oxidation of soil organic matter. The averaged $N_2O$ emission from the oxidation of soil organic matter was 4.83 kg N $ha^{-1} yr^{-1}$, and we used this value to determine the ratio between emission of $N_2O$ from oxidation of soil organic matter and the simultaneous emissions of $CO_2$ (Kg N $ha^{-1} yr^{-1}$ emitted per t $CO_2$ $ha^{-1} yr^{-1}$). We estimated $N_2O$ emissions from soil oxidation for each zone in Staten Island by applying the ratio to the $CO_2$ emissions estimated by SUBCALC for the zone.



| Zone | LandUse | Soil organic matter (%) | Area (ha) |
|---|---|---|---|
| 1 | Crop | 11.49 | 837 |
| 2 | Pasture | 11.49 | 272 |
| 3 | Crop | 24.22 | 747 |
| 4 | Crop | 32.07 | 852 |
| 5 | Crop | 28.46 | 1,022 |

**Figure 7** GHG emission zones on Staten Island

**Table 2** Delta restored wetlands $CO_2$ and $CH_4$ annual flux rates

| Wetland | Island | $CO_2$ (t C $ha^{-1}$ $yr^{-1}$) | $CH_4$ (t C $ha^{-1}$ $yr^{-1}$) | Reference |
|---|---|---|---|---|
| East Pond | Twitchell | -4.12 | 0.56 | Anderson et al. 2016 |
| West Pond | Twitchell | -4.10 | 0.46 | Oikawa et al. 2017 |
| East End | Twitchell | -5.5 | 0.28 | Oikawa et al. 2017 |
| Mayberry | Sherman | -2.81 | 0.59 | McNicol 2017<br>Oikawa et al. 2017 |

### *Rice GHG Fluxes*

We estimated the annual net GHG emissions for rice based on measurements reported for $CO_2$ and $CH_4$ by Knox et al. (2016), and for $N_2O$ by Ye et al. (2016). $CO_2$ and $CH_4$ fluxes were monitored by Knox et al. (2016) in a rice paddy on Twitchell Island for 6 years (2009–2015) and included carbon exported as harvested grain. To estimate GHG emissions from rice, we used the 6-year average annual $CO_2$ and $CH_4$ combined emissions of 10.4 t $CO_2$-e $ha^{-1} yr^{-1}$. We estimated the annual $N_2O$ emissions for rice in each zone of Staten Island where rice was introduced using the equation from Ye et al. (2016) that relates $N_2O$ emission to soil organic matter.

### *Wetland GHG Fluxes*

To estimate GHG fluxes of wetlands, we used data for four restored wetlands on Sherman and Twitchell islands (Table 2). Both Delta islands are located southwest of Staten Island (Figure 1). For each of the restored wetlands, we averaged all available annual data for $CO_2$ and $CH_4$ emissions, both expressed in t $CO_2$-e $ha^{-1}$ $yr^{-1}$. Wetlands were, on average, a GHG source of 2,60 t $CO_2$-e $ha^{-1} yr^{-1}$. All wetlands showed a large range in annual GHG balances, and inter-annual variability as large as differences among restored wetlands.

### *Uncertainties in Emissions and Emission Reductions*

We determined uncertainty for each scenario as the square root of the summed errors for each of the GHG fluxes. We weighted the uncertainty of each flux for its contribution to the total flux, and only considered fluxes that contributed more than 5% (Deverel et al. 2017). We calculated uncertainties in emission reduction for baseline and alternative scenarios. When we used models to predict fluxes, we included uncertainty for model inputs and structural errors obtained from the comparison of modeled and observed values. Uncertainty was expressed for the 90% confidence interval of mean values.

### Economic Methods

To assess economic consequences, we used the Delta Agricultural Production (DAP) model, a regional agricultural production and economic optimization model that simulates farmers' decisions based on actual observations. The original DAP model was developed in 2006 by researchers in the Center for Watershed Sciences and the Department of Agricultural and Resource Economics at the University of California at Davis. The current version is disaggregated for 53 Delta islands and calibrated based on 2007 crop acreage. The DAP model uses Constant Elasticity of Substitution production functions for every crop, and self-calibrates to replicate observed input use and output using the method of Positive Mathematical Programming (Howitt 1995).

A significant drawback for traditional linear programming optimization are the discontinuous jumps resultant from lack of accounting for declining returns to scale or increased production effects. For instance, under the assumption that farmers are profit-maximizing, a traditional optimization model will simply allocate all available land to the crop that produces the highest profit, which is not observed empirically. One of the advantages of using Positive Mathematical Programming specification is its smooth response to scenarios grounded in economic theory, which produces more realistic results (Howitt 1995). The DAP model therefore produces results that replicate base year marginal conditions that might include inter-temporal effects of crop rotation, proximity to processing facilities, management skills, farm-level affects, and heterogeneity in soil and other physical capital.

The DAP model is programmed using the General Algebraic Modeling System (GAMS) and solved using the nonlinear solver CONOPT-3. The most reliable estimate of regional land use in the Delta was carried out in 2007 by the CA Department of Water Resources, which along with the UC Davis Cost and Return Studies (*http://coststudies.ucdavis.edu/en/current/*), are the primary data sources in the DAP model.

All of our monetary estimates are expressed in 2007 US dollars for consistency with the prices, costs, and land-use data in the DAP model. All monetary adjustments were accomplished using the Bureau of Labor Statistics Consumer Price Index (CPI) Inflation calculator found at *https://data.bls.gov/cgi-bin/cpicalc.pl*.

We simulated a regional GHG offset market for wetlands in the DAP model as a source of revenue for land-owners. We set the carbon offset market price used to calculate revenue available to growers at \$9.69 per t $CO_2$-e in 2007 dollars. To simulate the net economic effects of wetlands, we used the operating costs of \$102.00 $ha^{-1} yr^{-1}$ from an estimate for a wetland on Twitchell Island.

For each land-use scenario, we set the rice and wetland extension to be fixed in the DAP model, and then allowed it to optimize the allocation of the remaining currently grown crops to maximize profit on Staten. We then compared these profit estimates, which contain wetland net revenue from the GHG offset market, to the profit in the baseline scenario. This provided an analysis of the economic effect for each of our land-use scenarios.

## RESULTS

### Greenhouse Gas Emissions and Emissions Reductions

To estimate GHG emissions reductions, we determined the net emission that resulted from the difference between baseline and reduced depth to groundwater and alternative land-use emissions (wetlands and rice). The average GHG flux rate of 2.6 t $CO_2$-e $ha^{-1} yr^{-1}$ used for wetlands represented large temporal and spatial variability among wetlands. For rice, GHG fluxes resulted from a multi-year study on Twitchell Island (Knox et al. 2016). Our $CH_4$ emissions for rice ranged from 60 to 200 kg C $ha^{-1} yr^{-1}$, compared with 206 to 440 in Ye et al. (2016) and 66 to 123 kg C $ha^{-1} yr^{-1}$ in Morris et al. (2017). Our estimates of $N_2O$ emissions in rice on Twitchell Island ranged from 0.75 to 1.68 kg N $ha^{-1} yr^{-1}$, based on Ye et al. (2016). Morris et al. (2017) measured $N_2O$ emissions of 1.2 to 3.7 kg N $ha^{-1} yr^{-1}$ in the same area on Twitchell Island. Our estimate of $N_2O$ emissions from soil oxidation for baseline conditions ranged from 2.8 to 10.4 Kg N $ha^{-1} yr^{-1}$. This estimate was consistent with values reported in the literature (e.g., Kasimir–

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Klemedtsson et al. 1997) and the default value for $N_2O$ emissions for oxidation of organic soils of 8 Kg N $ha^{-1} yr^{-1}$ used by the Intergovernmental Panel on Climate Change (IPCC 2006).

Estimated GHG emissions for the baseline scenario averaged over a 50-year period were 75,300 (±14,000) t $CO_2$-e $yr^{-1}$ (Table 1, Figures 8 and 9). Scenario 1, in which groundwater levels were typical of a central Delta island, resulted in the highest estimated emissions of 100,000 (±18,000) t $CO_2$-e $yr^{-1}$ (Table 1, Figure 8 and 9) and 33% higher GHG emissions than the baseline. Simulated GHG emissions for Scenario 2 were lower because of the simulation of a shallower groundwater table at 60 cm, and averaged 50,700 (±9,000), 33% less than the baseline GHG emissions. Overall, there is a large range of emissions, which results from varying depth to groundwater that ranges from circa 48,000 to 105,000 t $CO_2$-e $yr^{-1}$ (Table 1, Figures 8 and 9). The estimated emission decline with time (Table 1, Figure 8) results from decreasing soil organic matter content for baseline conditions (see Deverel and Leighton 2010).

For Scenario 3, in which 1,787 ha were simulated as converted to wetlands, we estimated net island GHG emission of 32,500 (±8,000) t $CO_2$-e $yr^{-1}$ (Table 1, Figures 8 and 9). For the rice–wetland mosaic in Scenario 4, the estimated GHG emissions were 42,400 (±6,000) t $CO_2$-e $yr^{-1}$ (Table 1, Figures 8, and 9). For Scenario 5, where we simulated 1,433 ha of rice on the highest organic matter soils, we estimated a net GHG emission of 53,600 (±7,000) t $CO_2$-e $yr^{-1}$ (Table 1, Figures 8 and 9). Compared to baseline emissions, conversion to wetlands on 48% of the island reduced emissions by about 43,000 (±13,000) t $CO_2$-e $yr^{-1}$ or 57%. The conversion to a mix of wetland and rice on the same area reduced emissions by about 33,000 (±8,000) t $CO_2$-e $yr^{-1}$ (44%), and planting rice on 38% of Staten Island resulted in a reduction in GHG emissions of 22,000 (±5,000) t $CO_2$-e $yr^{-1}$ or 30% (Figure 9b).

## Results of Economic Analysis

Table 3 shows the economic effects of the land-use Scenarios 3, 4, and 5 as a profit difference relative to the baseline after the DAP-allocated remaining traditional crop areas based on profit optimization. These results include wetland payments to land-owner from the simulated GHG compliance offset market. Scenario 3, which included 1,780 ha of wetlands, resulted in a substantial decrease in farm profitability of over 78% relative to baseline. In

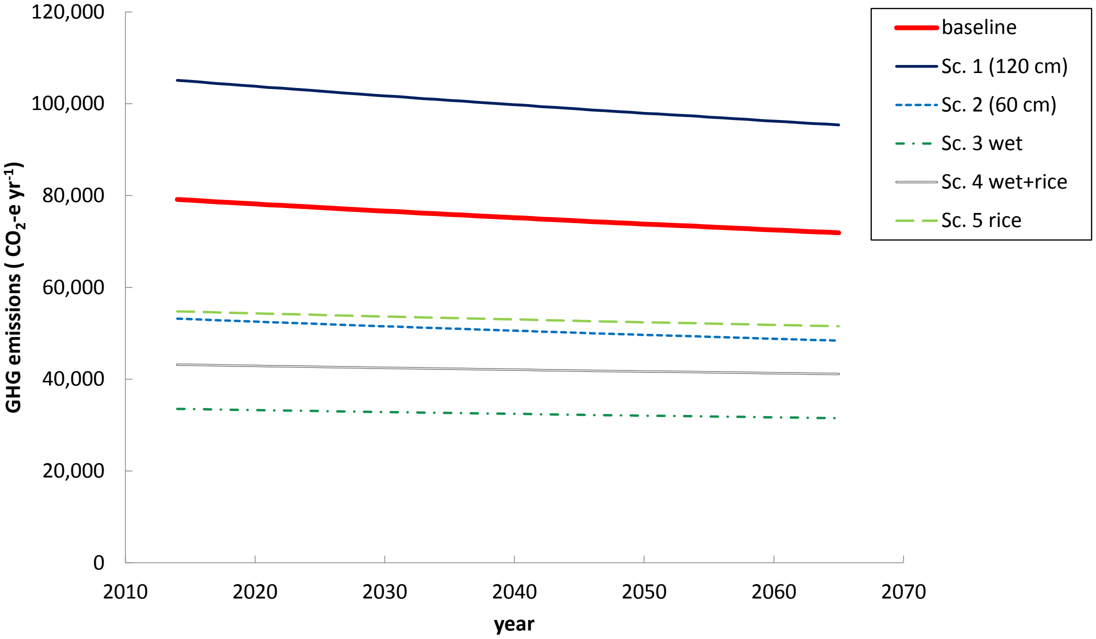

**Figure 8** Estimated emissions for baseline and water-management scenarios. Scenarios reflect varying depth to groundwater. Depth to groundwater varied from 120 cm (Scenario 1) to 60 cm (Scenario 2).

Scenario 4, in which a mixture of rice, wetlands, and currently grown crops were simulated, there were relatively small estimated decreases to farm profits. For Scenario 5, in which 1,433 ha of rice were simulated, we estimated a 12% increase in profitability relative to baseline.

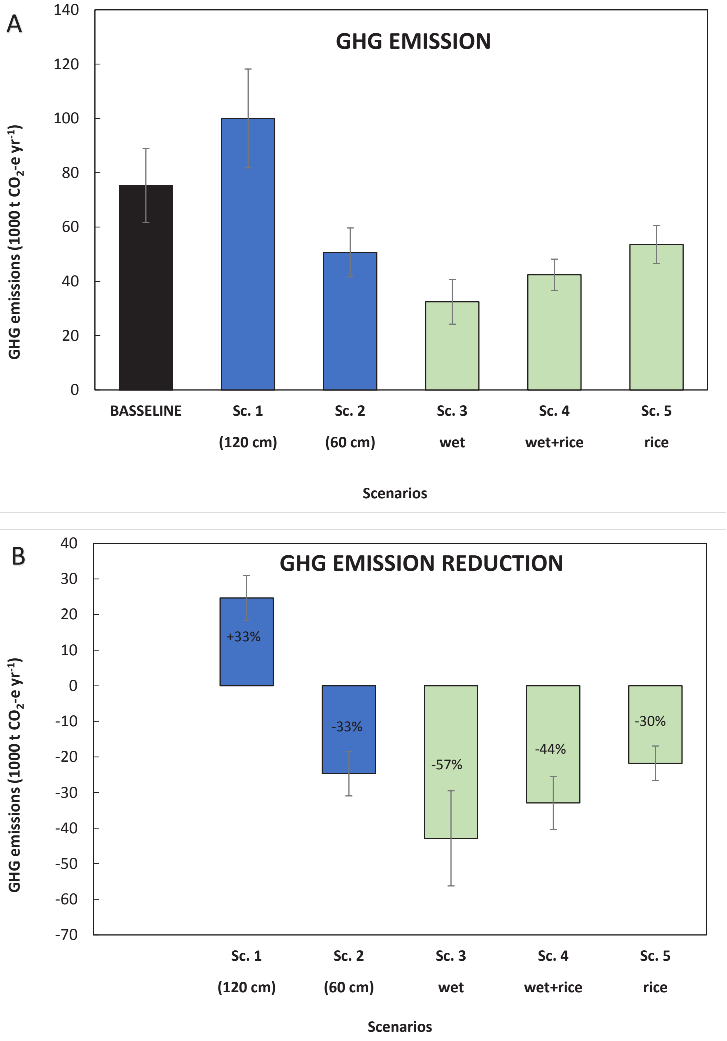

**Figure 9** (**A**) Net annual GHG emissions for the baseline and different scenarios (Sc.). Scenarios 1 and 2 represent management scenarios for different water depths (DTW). Scenarios 3, 4, and 5 represent land-use scenarios including wetland (wet) and rice. (**B**) Reduction of GHG emissions for scenarios including different management and land use compared to the baseline. Percent reduction compared to baseline emission is shown for each scenario.

**Table 3** Profit difference of different land use from baseline scenario

| | Scenario 4 (Wetland) | Scenario 5 (Wetland and Rice) | Scenario 6 (Rice) |
|---|---|---|---|
| Profit difference from baseline scenario | −79% | −16% | 12% |

## DISCUSSION

Results of recent GHG emissions measurements and modeling for California indicate that, overall, agriculture is close to neutrality, or a small sink for GHGs, with an average net GHG removal of about 0.028 t $CO_2$-e $ha^{-1} yr^{-1}$ (Li et al. 2014). Our estimated GHG emissions on Staten Island under baseline agricultural conditions ranged from 20.2 (±3) to 21.22 (±4) t $CO_2$-e $ha^{-1} yr^{-1}$ during 50 years (Table 1). These values are in the range of measured and modeled GHG emissions from crops in Delta organic soils from about 7.4 to over 37 t $CO_2$-e $ha^{-1} yr^{-1}$ (Knox et al. 2015; Deverel and Leighton 2010). Thus, GHG emissions from the oxidation of Delta organic soils are several orders of magnitude larger than GHG emissions for California agriculture.

The primary factor that determined the variability of estimated baseline GHG emissions was depth to groundwater; reducing the depth to groundwater could substantially reduce GHG emissions on Delta islands. However, maintenance of shallower groundwater levels will result in greater evaporation of the shallow groundwater, and thus potentially contribute to greater groundwater and soil salinity (Gardner and Fireman 1958). Also, higher groundwater levels will be less suitable for growing crops that require deep root zones.

Even though substantial GHG reductions can be achieved through water table depth reductions, the highest GHG reductions for typical Delta islands such as Staten result from implementation of land-use changes (Table 1, Figure 9). The placement of alternative land uses in relation to soil organic matter content determines the magnitude of GHG emission reductions. The largest baseline emissions occur in the highest organic matter soils on southern Staten. Thus, we implemented wetland and/or rice cultivation in this area.

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Economic analysis indicates that conversion to rice and an admixture of rice and wetlands on highly organic soils has a small effect on farm profitability relative to baseline conditions and results in a large reduction in the island's net GHG emissions. However, conversion to a large area of wetlands substantially reduced profitability. Large-scale implementation of palustrine wetlands on Delta organic soil will thus necessitate additional income sources to maintain farm profitability. These may include higher GHG offset prices and inclusion of habitat mitigation credits.

For alternative land uses, we used published GHG emissions for rice and wetlands. For wetlands, the literature values resulted in estimation of wetlands being a net GHG source. However, wetland emissions are likely conservatively over-estimated because we included values where management practices and environmental factors resulted in low wetland productivity and high methane emissions. We posit that GHG emissions for wetlands on Staten will be similar to GHG emissions for the old and new Twitchell wetlands described in Knox et al. (2015) and will result in larger emissions reductions than those estimated here. Our study suggests that restored wetlands do not need to be GHG sinks to result in a reduction of GHG emissions in the Delta because large baseline GHG emissions would cease. Estimates can be improved by including small-scale temporal and spatial variability derived from additional GHG flux monitoring activity, model improvement, and additional quantification of the main drivers of GHG dynamics in restored flooded ecosystems.

Estimated GHG emission reductions will change if a different global warming potential for methane is considered (e.g., as in Neubauer and Megonigal 2015), and with further understanding of factors that control GHG dynamics and their long-term trends and evolution. Compared to other wetlands in North America, restored wetlands in the Delta exhibit elevated productivity and high $CH_4$ emissions (Bridgham et al. 2006).

Other agronomic and ecosystem factors such as subsidence, drainage, weed control, and habitat also require consideration on Delta farmed islands. Subsidence and associated seepage is a key factor that contributes to decreasing agricultural sustainability and levee vulnerability in the Delta (Deverel et al. 2015; Deverel et al. 2016b). Managed wetlands stop and reverse the effects of subsidence (Miller et al. 2008). Also data from Twitchell Island indicate that rice stops subsidence relative to traditional land use (Deverel et al. 2016a). Constructing wetlands and cultivating rice on southern Staten will provide substantial levee benefit over the long term because of the beneficial effects on seepage and subsidence, where vulnerability is the highest. As groundwater levels rise under wetlands and rice, seepage forces (as determined by calculation of exit gradients), which can threaten levee stability, will decrease (e.g., Deverel et al. 2014).

Drainage can be challenging where rice and wetlands are implemented in conjunction with other crops that require a drained root zone during the growing season. Effective maintenance of drainage ditches, strategic placement of rice and wetlands, and the ability of pump stations to effectively remove subsurface water will be the key elements for minimizing the effects of seepage to adjacent traditional crops.

Delta rice yields have generally been consistently profitable for Delta growers for the last 10 to 20 years, after the development of short-season and cold-tolerant varieties (e.g., M104). During a 2004–2005 assessment, rice was substantially more profitable than corn (Bachand & Associates et al. 2006) and can be as competitive as other traditional crops currently grown on Staten and throughout the Delta. Despite this, rice currently and historically has not been grown at significant levels; less than 2,000 ha. If the reason for this is not economical but based more on cultural values, further outreach and education could incentivize land-owners to grow larger proportions of rice in the Delta. However, previous work indicates that there is reluctance to invest in the substantial changes in infrastructure required for rice cultivation (Bachand & Associates et al. 2006). Rice generally requires substantial one-time infrastructural changes for leveling and berm construction, but experience on other islands where rice is grown (e.g., Bract Tract and Wright Elmwood Tract) indicates that little additional work is needed for maintenance of berms and level conditions. Similarly, leveling and berm construction are required for wetlands.

The creation and maintenance of water bird habitat has been a key management objective for Staten Island, which provides the primary Delta fall and winter foraging habitat for the Greater Sandhill Crane. Several authors reported Greater Sandhill Cranes' affinity for rice fields in California and the Delta for foraging and roosting (Littlefield 2002; Shaskey 2012; Ivey et al. 2011). Rice also provides summer and winter bird habitat (Bachand & Associates et al. 2006).

Designing policy mechanisms entails an analysis of the benefit and cost trade-offs. Our methods not only reveal the GHG and economic trade-offs for a representative Delta island, but additionally provide an example of how inter-disciplinary applied research can be utilized to assess the feasibility of broader Delta land-use policies. In our scenarios, we chose an allocation of wetlands and rice, and then estimated the trade-offs from those decisions. Our approach can be replicated when policy planners evaluate alternative land-use scenarios.

Moreover, the Staten Island mosaic serves as a relevant example for multiple central Delta islands where there are variations in the depth of subsidence (Figure 1) and soil organic matter content (Figure 1, Deverel and Leighton 2010). For example, on Terminous Tract, Tyler Island, Bouldin Island, Venice Island, Orwood Tract, and Palm Tract, the organic-matter content varies substantially. A similar approach could potentially be adapted for these islands on which traditional crops could be grown on the lower organic-matter soils, and rice and wetlands could be grown and created, respectively, on higher organic-matter soils, such that overall income for the island is not substantially different from the baseline condition.

## CONCLUSIONS

Though management practices such as maintaining shallower groundwater through drainage management can substantially reduce GHG emissions, alternative land uses are required for substantial GHG removals for typical Delta islands such as Staten. Conversion of Staten Island to a mosaic of wetlands and various combinations of crops that include rice could substantially reduce overall GHG emissions. Converting part of the island to wetlands creates a maximum reduction in GHG emission, but also in profit. Our analysis indicates that if a mixture of rice and wetlands is used, farm profits decreased slightly, and GHG emission reduction is significant. Cultivating rice on about one third of the island reduced GHG emissions and increased profit.

Measured and modeled baseline GHG emissions from Delta organic soils were substantially greater than in California mineral soils devoted to agriculture. Therefore, implementation of alternative land-use practices on Delta organic soils makes sense from a Californian agricultural GHG reduction standpoint. Restored flooded ecosystems don't need to be GHG sinks to represent a GHG benefit when compared to current large GHG emissions. Though several factors influenced net GHG removals and emissions estimates for Staten Island, the most important factor is baseline GHG emissions. Areas can be carefully selected to maximize GHG emission reduction in the Delta, including differences in GHG emission rates of both current and restored flooded land use where baseline emissions are large on highly organic-matter soils. Rice and wetlands were thus simulated on the highly organic-matter soils with the largest baseline emissions on Staten Island. Rice and wetlands will also stop subsidence (in the case of rice) and reverse the effects of subsidence (in the case of wetlands) on the most subsided parts of the island, and thus reduce subsidence and seepage threats to levee stability.

Our results provide insights about economic and GHG emissions trade-offs for a central Delta island and provide an example of how inter-disciplinary applied research can be utilized to scope the feasibility of broader Delta land-use policies for greater sustainability. Moreover, the Staten Island mosaic serves as a relevant example for many central Delta islands where there is a variation in depth of subsidence and soil organic-matter content and where a similar approach could potentially be adopted.

## ACKNOWLEDGEMENTS

We are grateful to The Nature Conservancy for funding for the work described here. Moreover, Michelle Passero, and Alex Leumer of The Nature Conservancy; Leo Winternitz formerly with The Nature Conservancy; and Brent Tadman and

Dawit Zeleke of Conservation Farms and Ranches were instrumental in providing help and support for the study. The authors also thank Dr. Leslie Butler and Dr. Douglas Larson at the UC Davis Department of Agricultural and Resource Economics and two anonymous reviewers for helpful insights and suggestions.

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