



## Incorporating climate change with conservation planning: a case study for tidal marsh bird conservation in Delaware, USA

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**ABSTRACT:** Northeastern USA tidal marshes provide critical ecological services, including carbon sequestration, water filtration, storm protection, erosion control, and wildlife habitat. Regardless of the services provided, salt marshes have been filled, drained, and degraded since European settlement, and the unique wildlife dependent on these ecosystems requires immediate conservation action. Furthermore, global sea level rise has become the foremost cause of contemporary and future marsh loss. Sea levels have risen approximately 2 mm/year over the last century and predicted marsh losses due to sea level rise are estimated to be 0.5–1.5% annually. Increases in marsh flooding from sea level rise creates a real and immediate challenge to tidal marsh bird persistence, and uncertainties surrounding sea level rise must be integrated into conservation decisions to achieve smart and proactive conservation planning. Decisions about how to allocate limited conservation funding are often subjective and lack quantitative and repeatable methodologies. To assist with prioritizing salt marsh habitat protection, we tested two quantitative methods (benefit targeting and binary linear programming optimization) to determine the best combination of unprotected tidal marsh parcels that would yield the greatest conservation benefit. We used three budget level scenarios (\$10M, \$15M, and \$20M) to develop budget specific parcel portfolios based on benefit targeting and optimization, and used tidal marsh obligate breeding bird density as our conservation target. We used three sea level rise scenarios (0.5 m, 1.0 m, and 1.5 m) to estimate the land cover types that would remain within each selected parcel following a rise in sea level. The optimization method selected more

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**abstract continued**

parcels, protected more marsh area, and conserved more tidal marsh obligate birds than the more traditional benefit targeting method. Total marsh area ranged from 7.2–9.6% greater and bird density ranged from 7.3–12.8% greater given the optimization method. When benefit targeting and optimization protected the same number of birds, optimization provided a cost savings of \$1.75M–\$2.9M. All sea level rise scenarios inundated greater than 95% of the wetland area on selected parcels. Agricultural land had the greatest amount of area remaining of any land cover type in all scenarios, ranging from 79.9 ha, 82.0% of total portfolio area (\$10M–1.5 m scenario), to 648.7 ha, 70.8% of total portfolio area (\$20M–0.5 m scenario). Optimization models can be used to develop comprehensive strategies that protect marshes with current core tidal marsh bird populations. However, increasing rates of inundation from sea level rise will likely lead to losses of existing wetland areas. The potential future benefits of adjacent agricultural lands to tidal marsh birds through marsh migration should be incorporated into optimization models for more effective conservation planning and spending of limited financial resources.

*Keywords: benefit targeting, binary linear programming, bird density, conservation planning, marsh birds, conservation optimization, sea level rise, tidal marsh*

**INTRODUCTION**

Tidal marsh ecosystems provide essential ecological services including; protecting shorelines from erosion and strong wave dynamics, serving as areas for flood storage, acting as nursery habitat for marine organisms, and improving water quality (Greenburg 2006). Despite these critical functions, few marshes remain in pristine condition and the majority of marshes have historically experienced severe alterations. Development (Takekawa et al. 2006), agriculture (Dreyer and Niering 1995), ditching and channelization (Daiber 1986), marsh burning (Nyman and Chabreck 1995), invasive species (Benoit and Askins 1999), pollutants (Bertness 1999), and global climate change (Arp et al. 1993), have contributed to extensive marsh loss and degradation of remaining areas (Tiner 1984, Dahl 1990).

Of the 25 vertebrate species restricted to salt marsh habitats, 21 species or recognized subspecies are considered endangered, threatened, or of other heightened conservation concern in the United States (Greenburg 2006). Tidal marsh birds are of particular concern, as population estimates or trends are unknown and much of the habitat may be inundated in the near future. Several avian species spend their entire annual life cycle in tidal marshes and nest near or directly on the marsh surface (e.g., Clapper rail [*Rallus longirostris*], Willet [*Tringa semipalmata*], Saltmarsh sparrow [*Ammodramus caudacutus*], and Seaside sparrow

[*A. maritimus*]), therefore their reproduction is directly tied to flooding events (Gjerdrum et al. 2005, 2008, Shriver et al. 2007). Increases in flooding from sea level rise pose real immediate challenges to the persistence of tidal marsh bird populations as 0.5–1.5% of global marshes are predicted to be lost annually due to inundation (Shriver and Gibbs 2004, Greenburg 2006, Dahl and Stedman 2013).

Conservation of salt marsh habitat is a high conservation priority, particularly in light of accelerated sea level rise (Douglas 1991, IPCC 2007, Rahmstorf 2007). Furthermore, the U.S. has a greater opportunity for tidal marsh conservation than other nations, given one-third of the global extent (4,500,000 ha) of tidal marshes are located along the country's Atlantic and Gulf coasts (Greenburg 2006). To prepare for the challenges tidal marshes face from global climate change, conservation decisions must be made using objective, quantitative and repeatable methods that incorporate sea level rise uncertainties. Such decision-making should effectively prioritize land acquisitions and efficiently allocate limited conservation funds while proactively addressing potential future habitat changes.

Two selection methods used by conservation planners to identify priority projects for land acquisition or easement opportunity vary in their capacity to select cost-effective projects given the fiscal constraints of limited budgets. Benefit targeting is a rank-based method that uses a

“greedy agent” algorithm to acquire parcels with the highest conservation value, independent of project costs, until a specified budget is exhausted. These “greedy heuristic algorithms” are routinely used in conservation planning for reserve site selection (Margules et al. 1988, Pressey and Nicholls 1989, Bedward et al. 1992, Freitag et al. 1997, Cabeza and Moilanen 2003) and, given the availability of avian data, these taxa are well represented as a measure of the conservation benefit in reserve selection projects (Sætersdal et al. 1993, Fairbanks et al. 2001). Although benefit targeting continues to be the most used method for developing conservation planning strategies, the method’s outcomes can lead to inefficient monetary spending and suboptimal conservation gains (Underhill 1994, Rodrigues and Gaston 2002, Messer 2006, Messer and Allen 2010, Duke et al. 2013). Alternative methods to benefit targeting include linear, binary, and mixed integer programming. These optimization algorithms find solutions that minimize the expenditure of financial resources while simultaneously maximizing a desired conservation target (Allen et al. 2011, Kaiser and Messer 2011). Optimization algorithms are being used more frequently to answer a variety of conservation questions (Williams and ReVelle 1998, Haight et al. 2004, Crossman and Bryan 2006, Martin et al. 2007, Downs et al. 2008, Stralberg et al. 2009, Fooks and Messer 2012, Fooks and Messer 2013).

Herein, we present a case study that compares the site prioritization between benefit targeting and optimization and then determines the future persistence of the selected parcels given three sea level rise scenarios and the implications for the tidal marsh bird community. Our specific objectives were to: 1) determine the tidal marsh areas in Delaware that support the greatest density of breeding tidal marsh obligate birds, 2) identify the extent of protected and unprotected salt marsh habitat in the state, 3) identify and compare benefit targeting- and optimization-selected parcel portfolios that maximize bird density on unprotected marsh habitat in three budget scenarios, and 4) determine the effect of three sea level rise scenarios on the proportion of land cover types within the optimized parcels.

## METHODS

### Parcels with Unprotected Marsh

To determine the extent of unprotected marsh in Delaware’s Kent and Sussex counties, we assessed publicly available geographic information systems (GIS) data from the Protected Areas Database (PAD) and the National Conservation Easement Database (NCED) (Data Basin - Conservation Biology Institute 2012). The PAD-US 1.1 - Conservation Biology Institute Edition (CBI Edition) is currently the most comprehensive geospatial dataset of U.S. protected areas. The NCED compiles conservation easement information from land trusts and public agencies and is the first such national database.

We used ArcMap10 (ESRI 2011) to overlay PAD-US 1.1 (CBI Edition) and NCED (Version 1, 2011) data on U.S. Fish & Wildlife Service (USFWS) National Wetlands Inventory (NWI) estuarine emergent marsh spatial data (USFWS 2012). We evaluated the extent of marsh habitat currently protected through ownership or conservation easements and used a series of geoprocessing tools to identify and extract marsh areas currently unprotected. We obtained geospatial land parcel data for Kent and Sussex counties from the Delaware DataMIL (Delaware Geological Survey 2012) and overlaid the data on the unprotected marsh spatial information. We identified the parcels that contained unprotected marsh and calculated marsh area for each parcel.

### Parcel Conservation Easement Costs

We calculated easement costs of parcels with unprotected marsh using values from an existing hedonic analysis, originally developed to estimate agricultural easement values (Allen et al. 2006). Allen et al. (2006) calculated regression coefficients from 501 parcels previously acquired by the state of Delaware for agricultural lands conservation to estimate easement costs of 1,095 unprotected parcels not formally appraised in Kent County (2006). We included the following variables relevant to calculating marsh conservation easement costs in our linear cost equation: county, tillable ha, tillable ha<sup>2</sup>, forest ha, forest ha<sup>2</sup>, wetland ha, wetland ha<sup>2</sup>, year 2001, distance to shore (km), and distance to urban area (km) (Table 1). The county variable

accounted for each easement’s initial base price and an additional \$100,661 was added to easement costs to control for market inflation relative to 1995, the baseline year analyzed in the hedonic analysis (Allen et al. 2006).

We estimated land cover for each parcel in ArcMap 10 (ESRI 2011) using 2007 Delaware land use/land cover (LU/LC) geospatial data (Delaware Geological Survey 2012). We defined our land cover classes as tillable areas, forested areas (including deciduous, evergreen, and mixed forest), and wetland areas (including all non-tidal and tidal wetland classes). We used the Delaware state boundary line to calculate distance to shore and the boundaries of incorporated municipalities to calculate distance to urban area (Delaware Geological Survey 2012). We multiplied parcel variable values by their associated monetary value listed (Table 1), and summed or subtracted where appropriate to obtain an estimated parcel easement cost.

### Bird Surveys

We conducted this study in tidal salt marsh habitat in Kent and Sussex counties, Delaware. These marshes are classified as Northern Atlantic Coastal Plain Tidal Salt Marsh and range from the southern coast of Maine to the Chesapeake Bay, Virginia (Comer et al. 2003). This system of salt marshes occurs on the bayside of barrier beaches and along the outer mouth of tidal rivers where salinity has not been strongly impacted by freshwater.

We used a two-stage cluster sampling design to randomly distribute survey points within the Saltmarsh Habitat & Avian Research Program (SHARP, www.tidalmarshbirds.org) study area (Johnson et al. 2009), which extends through Bird Conservation Region (BCR) 30 and north to Lubec, Maine. BCR 30, also known as the New England/ Mid-Atlantic Coast BCR, is a bird conservation planning

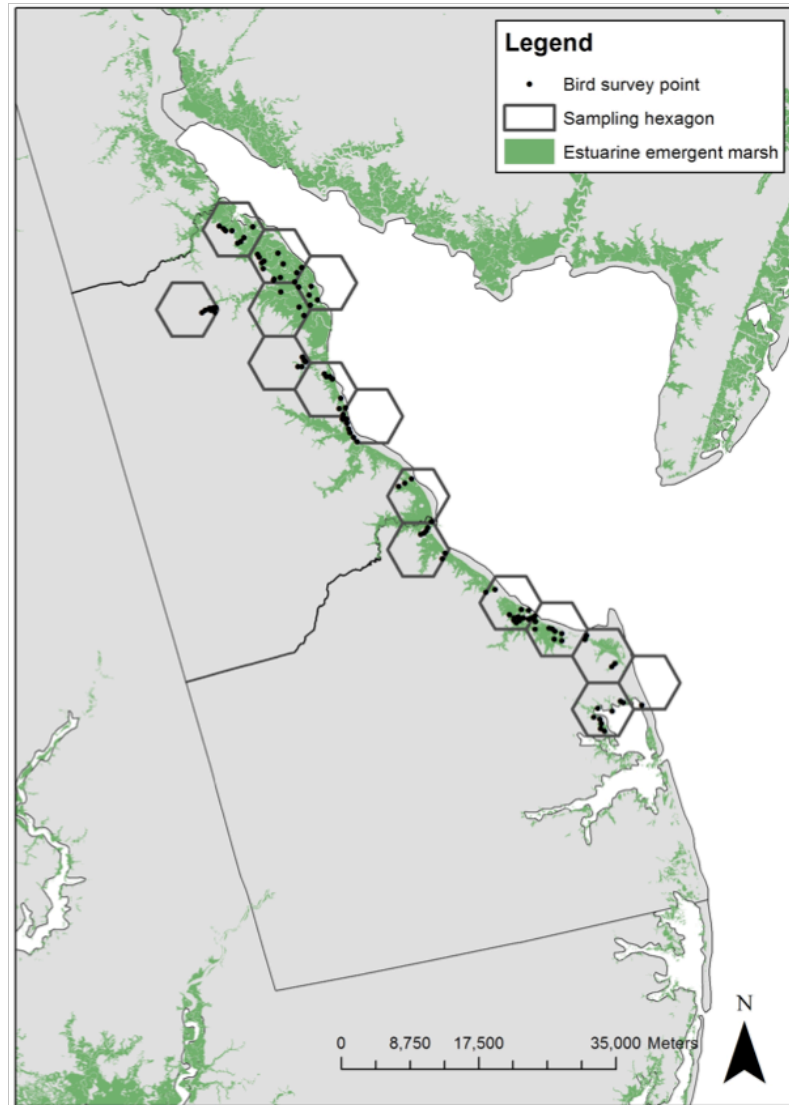
**Table 1: Hedonic analysis variables and associated values and interpretation used to calculate marsh conservation easement costs. Modified from Allen et al. 2006.**

Variable	Value	Interpretation
County	+ \$157,629.09 (Kent) + \$193,107.05 (Sussex)	County location constant
Tillable ha	+ \$ 7,289.02	Increase per tillable hectare
Tillable ha <sup>2</sup>	- \$ 13.37	Value increases at a decreasing rate when the number of tillable hectares increases
Forest ha	+ \$ 9,111.42	Increase per forest hectare
Forest ha <sup>2</sup>	- \$ 59.90	Value increases at a decreasing rate when the number of forest hectares increases
Wetland ha	+ \$ 3,644.46	Increase per wetland hectare
Wetland ha <sup>2</sup>	- \$ 17.77	Value increases at a decreasing rate when the number of wetland hectares increases
2001	+ \$100,660.62	Inflation (relative to 1995)
Distance to shore (km)	- \$ 4.77	Decrease for each kilometer away from the shore
Distance to urban area (km)	- \$ 15.71	Decrease for each kilometer away from the nearest urban area

region administered by the Atlantic Coast Joint Venture that extends from coastal Virginia through southern coastal Maine (Steinkamp 2008). The primary sampling units (PSUs) selected during the first-stage were 40km<sup>2</sup> hexagons used by the National Marsh Bird Monitoring Program (Seamans 2011), (Figure 1). During the second-stage of site selection, we used NWI estuarine emergent marsh geospatial data to randomly distribute the survey points (secondary sampling units [SSUs]) across marsh habitat within selected PSUs (USFWS 2012).

We used a generalized random tessellation stratified (GRTS) survey design in Program R using the spsurvey package to generate survey points (Kincaid and Olsen 2012, R Core Team 2010). Samples from GRTS survey designs emphasize spatial-balance, exhibiting spatial density patterns that closely mimic the spatial density patterns of the resource. We randomly located up to 10 survey points in each hexagon within estuarine emergent marsh. Points were at least 400 m apart to ensure independence (Conway 2011).

**Figure 1: Bird sampling locations for this study in Kent and Sussex counties, Delaware, USA. Hexagons are the primary sampling units, n = 15, and bird survey points are the secondary sampling units, n = 102.**





Trained field technicians collected bird survey data during the 2011 avian breeding season (May–July) at 102 survey points in Delaware for SHARP. At each survey point, field technicians conducted point-count surveys following the Standardized North American Marsh Bird Monitoring Protocol (Conway 2011). We conducted bird surveys from 30 minutes prior to sunrise and completed surveys before 11:00 a.m. We visited each survey location three times during the breeding season and we did not survey for breeding birds when wind speed was greater than 12 mph or during sustained rain or heavy fog. Each survey consisted of a five-minute passive listening period during which we recorded all individual birds seen or heard utilizing the marsh in one of three distance categories: 0–50 m, 50–100 m, 100+ m. We did not record species flying over the survey area or not actively foraging within the marsh.

### Conservation Benefits

We used SHARP’s Delaware bird survey data to calculate Clapper rail, Willet, Saltmarsh and Seaside sparrow densities based on point-count detections from the 0-50 m and 50-100 m distance categories. We estimated bird density (birds/ha) as the total number of individuals detected for the four species combined. We used the survey data to determine the maximum number of individuals detected across the three surveys at each survey point. We summed the maximum count values within a hexagon and divided by total survey area to calculate bird density (birds/ha) within each hexagon. Total survey area was calculated by multiplying the area of the point-count circle (radius = 100m) by the number of points surveyed within the hexagon. We used the mean bird density for surveyed hexagons to estimate bird density in unsurveyed hexagons. To calculate the parcel-specific bird density for estuarine emergent marsh, our “conservation benefit,” we multiplied the bird density estimate by the area of unprotected marsh within the parcel.

### Parcel Selection

We used benefit targeting and binary linear programming optimization and compared the selected parcels between the two methods to determine which method provided the greatest conservation benefit. The benefit targeting method typically selects parcels to acquire based on benefit values and does not take into account easement or transaction

costs explicitly in the selection process. Parcels are listed in descending order of benefit value; the parcel with the highest benefit score is acquired first, and the process continues until the budget is exhausted. Binary linear programming optimization evaluates the conservation benefits of the entire parcel pool, as well as estimated costs and budget constraints, to select a combination of parcels that provides the greatest aggregate conservation benefit within the constraints (Messer 2006). Optimization selects parcels that contribute to achieving the maximum total benefit possible within the apportioned budget. Model output is restricted to the integers 0 and 1, where a value of 0 indicated parcel rejection for land acquisition and a value of 1 indicated parcel selection. The resulting binary portfolio represents the best use of conservation dollars to conserve important core areas of four of Delaware’s tidal marsh obligate bird species. The optimization model was expressed as,

$$\max(X) = \sum_{i=1}^I X_i A_i$$

The model was represented by  $i = 1, \dots, 1,447$ , which indicated an index representing the 1,447 land parcels available for purchase. Conservation benefit (parcel bird density) was represented as  $A_i$ , and  $X_i$  represented the binary (0, 1) variable for the  $i$ th parcel. The model was subject to a budget constraint, where  $C_i$  was the cost of the  $i$ th parcel, and  $B$  was the total available budget,

$$\sum_{i=1}^I C_i X_i \leq B$$

We used Analytic Solver Platform and Microsoft Excel to perform benefit targeting and optimization analyses (Frontline Systems 2013).

We used three budget scenarios (\$10M, \$15M, and \$20M) for each selection procedure and allocated the entire budget within each scenario to tidal marsh conservation. The base budget level (\$10M) represented the State of Delaware’s 2013 Open Space Preservation budget (State of Delaware - Office of the Governor 2012). The \$15M and \$20M scenarios were analyzed in addition to the base level to evaluate the relationship between selection methods with an increased budget. The greater budgets could also be used for multi-year portfolios. We included a transaction fee of \$15,000 per parcel, as well as removed parcels less than 0.40 ha (1 acre) in total area to facilitate model computability.

### Sea Level Rise Scenarios

To estimate the impact of different sea level rise scenarios on the land cover of the optimization-selected parcels, we grouped 2007 Delaware LU/LC classes into general categories and used ArcMap 10 to calculate changes in land cover area due to permanent inundation (Table 2; ESRI 2011, Delaware Geological Survey 2012). We calculated

land cover area within each optimal parcel under four sea level scenarios; current mean higher high water (MHHW), 0.5 m, 1.0 m, and 1.5 m above MHHW between current (2011) and 2100 (Delaware DNREC 2012). We used spatial polygons delineated from overlays by the Delaware Department of Natural Resources and Environmental Control to depict each sea level rise scenario (Delaware DNREC 2012).

**Table 2: General land cover categories used to evaluate the impacts of sea level rise on optimization-selected parcels. Categories were comprised of 2007 Delaware Land Use/Land Cover (LU/LC) classes (Delaware Geological Survey 2012).**

General land cover	2007 Delaware LU/LC class
Wetland	non-tidal emergent wetland
	non-tidal scrub/shrub wetland
	tidal emergent wetland
	tidal scrub/shrub wetland
Forested wetland	non-tidal forested wetland
Agricultural land	cropland
	mixed rangeland
	pasture
	shrub/brush rangeland
Forested upland	deciduous forest
	evergreen forest
	mixed forest
Developed/barren land	beaches and river banks
	farmsteads and farm related buildings
	mobile home parks/courts
	multi family dwellings
	other urban or built-up land
	recreational
	retail sales/wholesale/professional services
	single family dwellings
	tidal shoreline
	transitional (incl. cleared, filled, and gravel)
	utilities
Water feature*	bays and coves
	man-made reservoirs and impoundments
	natural lakes and ponds
	non-tidal open water
	tidal open water
	waterways/streams/canals

*\*Water features were present on optimal parcels, however, this general land cover was excluded from the sea level rise impact analysis since water features are already comprised of water.*

## RESULTS

### Parcels with Unprotected Marsh

We estimated the presence of 31,543 ha of salt marsh in Delaware with 22,148 ha protected and 9,395 ha unprotected. Unprotected marsh in Kent and Sussex counties totaled 6,129 ha of which there were 2,587 ha located on 947 parcels in Kent County and 3,542 ha located on 2,318 parcels in Sussex County (parcel total n = 3,265). We removed 1,818 parcels, each less than 0.40 ha in total area, from the parcel selection pool. Removed parcels contained 98 ha of total marsh (1.59% of the state's unprotected marsh habitat). In total, 1,447 parcels, 384 and 1,063 from Kent and Sussex counties respectively, were analyzed for parcel portfolio selection. The parcels contained 6,030 ha of unprotected marsh, ranging from 0 – 208.60 ha per parcel. Mean marsh area was 4.17 ha/parcel and median marsh area was 0.70 ha/parcel.

### Parcel Conservation Easement Costs

Easements in Sussex County were \$35,478 greater than those in Kent County before landscape variable costs were

considered. The greatest increases in parcel easement cost due to the land cover variables were \$885,311 for tillable area (182.69 ha), \$264,498 for forest area (113.05 ha), and \$24,831 for wetland area (198.05 ha). Price increases reflect the difference between the whole area variable rate (e.g., tillable ha) and the area<sup>2</sup> variable rate (e.g., tillable ha<sup>2</sup>). Maximum cost values deducted for the distance variables were \$59 (12.38 km from shore) and \$153 (9.73 km from an urban area). Total easement cost for parcels in the selection pool ranged from \$258,193–\$1,387,190, with a mean cost of \$344,324 and a median cost of \$298,381.

### Conservation Benefit

Tidal marsh obligate bird totals within the surveyed hexagons ranged from 0–126 individuals (Table 3). Bird density on surveyed hexagons ranged from 0.0–3.71 birds/ha (mean = 1.79 birds/ha, SE = 0.31). Bird density within parcels with unprotected marsh ranged from 0.0–643.53 birds/parcel (mean = 8.83 birds/parcel, SE = 0.81).

**Table 3: Summary bird survey data by hexagon collected at 102 survey points in Kent and Sussex counties, Delaware, from May–July 2011.**

Hexagon ID	Survey points	Survey area (ha)	Total birds	Mean birds/pt	Bird density (birds/ha)
68731	13	40.84	126	9.69	3.09
69123	7	21.99	0	0.00	0.00
69124	3	9.43	31	10.33	3.29
69517	5	15.71	13	2.60	0.83
69911	8	25.13	31	3.88	1.23
71485	9	28.28	105	11.67	3.71
71879	1	3.14	5	5.00	1.59
237327	8	25.13	24	3.00	0.95
237721	5	15.71	52	10.40	3.31
238507	7	21.99	9	1.29	0.41
239294	4	12.57	21	5.25	1.67
239687	6	18.85	58	9.67	3.08
240081	13	40.84	76	5.85	1.86
240475	4	12.57	9	2.25	0.72
240868	9	28.28	33	3.67	1.17



### Parcel Selection

At the \$10M budget level, benefit targeting selected 13 parcels to maximize bird density for a total portfolio cost of \$9,912,597. Parcels contained 1,068 total ha of marsh and 3,150 birds. Binary optimization selected 18 parcels for a total cost of \$9,972,390, a 0.6% change from the benefit targeting portfolio cost. The optimization portfolio contained 77 more marsh ha and 319 more tidal marsh obligate birds than the benefit targeting portfolio, representing increases of 7.2% and 10.1% in conserved habitat and bird density, respectively (Figure 2).

With the \$10M budget level, the five parcels with the greatest bird densities were selected by both methods (Figure 3; Table 4). Benefit targeting selected three unique parcels including the most expensive parcel (\$1,387,190) and binary optimization selected eight unique parcels (Table 4). For benefit targeting to reach the 3,469 bird-conservation benefit secured by the optimization portfolio, an additional \$2,888,894 was required to purchase 3 more top-ranked bird density parcels. For a final cost of \$12.9M, purchasing the top-ranked 16 parcels would conserve 3,513 birds on 1,208 marsh ha, exceeding the \$10M optimized portfolio by 44 birds and 63 marsh ha.

When we increased the budget to \$15M, the optimization portfolio conserved 4,343 birds on 1,501 marsh ha, an

increase of 12.8% and 9.6% in birds and marsh area, respectively, from the benefit targeting portfolio (Figure 2). Twenty-nine parcels secured the larger total conservation benefit in the optimization portfolio at an additional cost of \$118,279; 0.8% over the total cost of the 19 parcels in the benefit targeting portfolio (\$14,866,046). Of the six parcels selected by benefit targeting but not by optimization, three had easement costs over \$1M and all six cost over \$750,000 (Table 4). An additional \$2.7M would be needed for benefit targeting to match the 4,343 birds conserved by optimization.

At the \$20M budget level, optimization selected 7 more parcels and the portfolio cost an additional \$28,107 (\$19,973,643 total) compared to the 28 parcels chosen with benefit targeting (0.1% change). The additional conservation benefit garnered by the optimal parcel combination equated to 344 birds and 163 marsh ha, increases of 7.3% and 9.6%, respectively, over benefit targeting benefits. The five parcels unique to the benefit targeting portfolio supported bird densities ranging from 90.54–119.84 birds/parcel, while the 12 parcels unique to the optimization portfolio supported bird densities from 53.73–89.69 birds/parcel (Table 4). At an additional cost of \$1.75M, benefit targeting would match the ~5,100 birds conserved by the optimized portfolio.

**Figure 2: Percent change (increase) for three portfolio variables from the benefit targeting method to the optimization method, by budget scenario.**

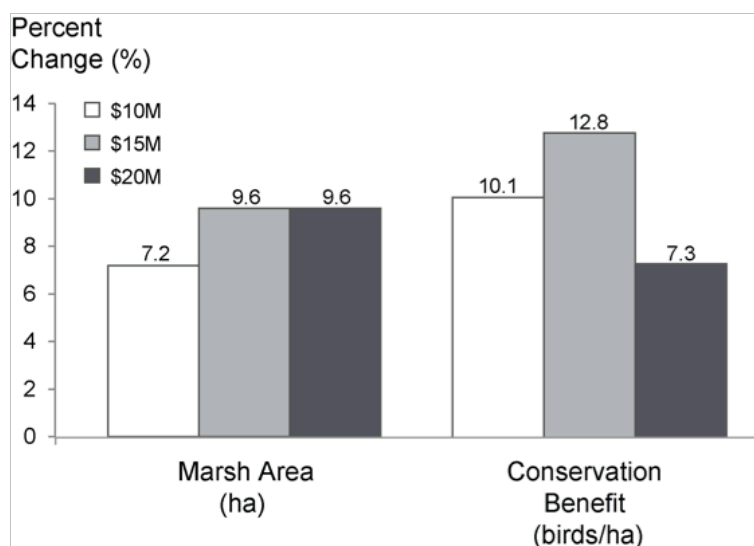
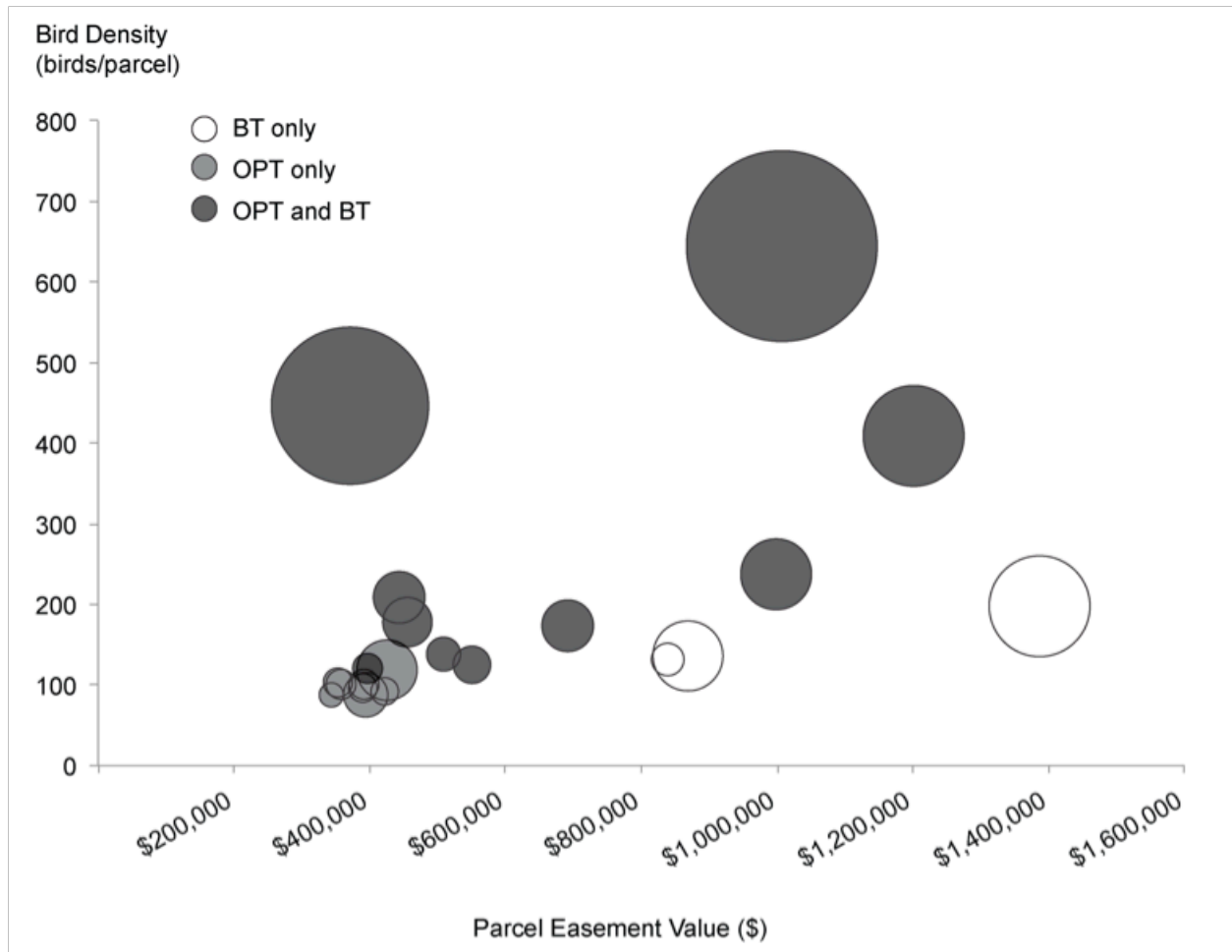


Figure 3: Conservation benefit (bird density) by parcel easement value for parcels selected in the \$10M budget scenario. Bubbles are shade-coded by selection method (benefit targeting [BT], optimization [OPT]) and bubble size represents parcel unprotected marsh area.



**Table 4: Parcel portfolios selected by two parcel selection methods, benefit targeting (BT) and binary linear programming optimization (OPT), for three budget scenarios (\$10M, \$15M, \$20M). A table of parcel landscape variables, conservation benefits, and easement costs is presented. Marsh area refers to unprotected marsh.**

BT	OPT	County/parcel ID (K [Kent]/ S [Sussex])	Total area (ha)	Marsh area (ha)	Bird density	Tillable area (ha)	Forest area (ha)	Wetland area (ha)	Dist to shore (km)	Dist to urban area (km)	Easement cost (\$)	Total cost (incl. trans fee; \$)
X	X	K/1-00-01300-01-0300-00001_3304	321.31	208.60	643.53	73.36	38.17	198.05	0.00	7.19	1,006,293	1,021,293
X	X	K/1-00-01300-01-0200-00001_3305	179.64	171.94	447.08	0.00	0.00	167.58	1.71	4.84	369,961	384,961
X	X	S/33500700000100_1146	251.88	110.20	409.24	92.22	22.72	130.57	1.48	0.00	1,201,231	1,216,231
X	X	S/33000400001700_93265	160.94	77.49	238.44	68.70	10.53	81.49	1.53	1.14	999,691	1,014,691
X	X	S/23501000000300_190798	57.39	56.49	209.79	0.00	0.00	56.66	1.19	1.19	443,195	458,195
X	X (20)	K/8-00-11400-01-0100-00001_75785	329.78	110.20	197.66	182.69	7.75	126.60	0.02	0.21	1,387,190	1,402,190
X	X	K/4-00-04900-01-0300-00001_37404	62.78	54.05	177.78	7.54	0.00	53.27	3.49	3.62	456,159	471,159
X	X	S/33000400000600_93358	127.99	56.43	173.64	28.83	4.37	63.86	3.30	2.82	691,686	706,686
X	X	S/23502300000300_190792	54.73	37.09	137.71	7.01	4.48	43.08	2.12	1.13	507,787	522,787
X	X (20)	S/33000300000500_93260	178.70	76.49	137.21	33.80	20.56	84.59	5.07	2.51	867,943	882,943
X	X (15/20)	S/23502300000202_189974	124.11	35.44	131.61	53.76	3.88	61.82	1.98	1.54	838,828	853,828
X	X	S/33001200001403_93322	74.86	40.86	125.73	16.83	2.46	39.06	3.09	0.61	549,912	564,912
X	X	S/23501700001500_189973	34.03	32.61	121.09	0.00	0.30	33.14	1.59	1.37	397,723	412,723
X (15/20)	X	K/7-00-10500-01-0200-00001_63336	85.44	65.95	118.29	0.00	0.46	65.98	5.21	1.29	425,551	440,551
X (20)	X	K/1-00-04000-01-0100-00001_3613	31.64	31.64	104.08	0.00	0.00	30.72	5.60	2.35	353,428	368,428
X (20)	X	S/33000500000100_93264	33.27	32.65	100.48	0.00	0.00	32.04	0.87	0.74	392,284	407,284
X (20)	X	K/5-00-16500-01-0200-00001_40362	32.72	32.61	100.34	0.00	0.00	32.51	2.53	2.16	357,958	372,958
X (20)	X	S/33000400001600_91672	31.55	31.37	96.52	0.00	0.00	31.11	2.53	2.12	389,899	404,899
X (20)	X	S/33000900000100_93317	35.18	29.87	91.91	5.05	0.00	29.96	1.26	0.74	423,480	438,480
	X	K/1-00-04100-01-0100-00001_	27.32	26.47	87.06	0.00	0.00	26.57	2.35	5.89	342,483	357,483
	X	K/5-00-12400-01-0401-00001_44363	49.08	48.38	86.79	0.03	0.06	48.30	0.29	2.12	393,671	408,671
X	X	K/5-00-12400-01-0301-00001_44355	109.66	68.42	122.74	28.08	3.74	73.19	0.00	0.90	657,222	672,222
X		S/33001200001400_93321	148.40	38.95	119.84	69.84	16.91	60.81	4.41	0.02	1,030,453	1,045,453
X		S/33400100000900_4688	161.63	32.26	119.78	70.08	47.97	40.34	3.09	0.61	1,156,219	1,171,219
X	X (20)	S/33000400001600_93266	88.83	36.32	111.75	41.54	7.29	39.26	2.53	2.12	752,413	767,413
X		S/23501600003600_189969	137.62	59.10	106.00	47.92	7.30	68.26	2.17	2.59	841,591	856,591
	X	K/4-00-03900-01-2600-00001_37211	26.18	26.18	86.13	0.00	0.00	25.52	6.16	1.77	339,681	354,681
	X	S/23402500002700_110688	70.69	43.84	78.63	0.00	0.00	35.95	0.00	5.87	401,723	416,723
	X	K/8-00-11300-02-1600-00001_75718	43.15	41.86	75.08	0.00	0.59	42.40	2.12	2.20	386,226	401,226
	X	S/33402500000200_1013	49.21	41.23	73.97	0.00	0.00	40.78	0.00	4.47	412,765	427,765
	X	S/33000500000101_92853	23.25	22.96	70.65	0.00	0.00	23.17	0.87	0.74	368,656	383,656
	X	S/23000300000900_93325	21.44	21.25	65.40	0.00	0.00	20.95	0.16	0.00	362,316	377,316
	X	S/33000500000600_93145	21.29	20.05	61.69	0.00	0.00	21.29	0.71	0.27	363,285	378,285
	X	S/33000500000401_93147	21.59	17.55	54.00	0.01	0.06	21.50	0.50	0.00	364,534	379,534
	X	S/23000100000100_93308	17.48	17.46	53.73	0.00	0.00	17.37	1.13	0.43	351,700	366,700
X		S/23000300000900_93328	104.65	33.59	103.36	48.69	7.96	47.57	0.82	0.00	818,872	833,872
X	X	S/13400800004200_55132	163.27	55.35	99.28	0.00	37.24	68.61	0.00	1.17	716,419	731,419
X		K/1-00-00300-01-1400-00001_2261	144.65	50.48	90.54	86.96	0.00	52.30	4.88	2.67	932,947	947,947
	X	S/33000400000700_93259	127.97	50.00	89.69	23.24	1.02	57.65	3.30	2.82	616,151	631,151
X	X	S/330005000002400_93271	55.55	28.93	89.02	25.14	0.09	28.65	0.74	0.18	559,202	574,202

### Sea Level Rise Scenarios

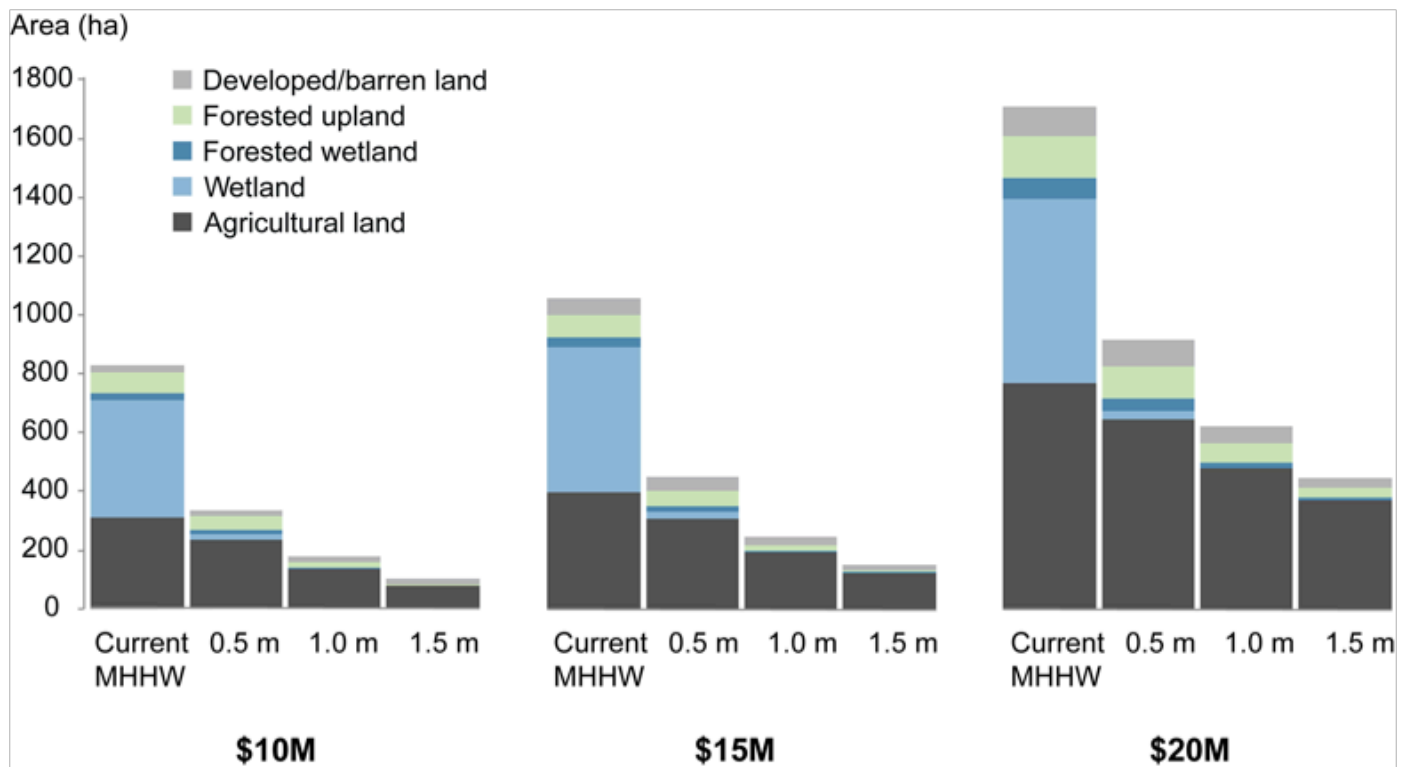
Wetlands occupied approximately 50% of the portfolio area at current MHHW for the \$10M and \$15M portfolios, 397.47 ha and 495.93 ha, respectively, and 37% for the \$20M portfolio (627.67 ha; Figure 4). For all budget levels, over 95% of the initial wetland area was inundated with a 0.5 m rise in sea level and 100% was inundated with a 1.0 and 1.5 m rise (Table 5). The largest amount of wetland area remaining following inundation was 30.68 ha in the \$20M–0.5 m scenario, equal to 3.4% of the portfolio’s total area (Figure 4).

Agricultural land accounted for 37–45% (395.23–772.84 ha) of the initial portfolio area(s) at current MHHW (Figure 4). The proportion of agricultural lands increased with increasing magnitude of sea level rise and occupied the largest area relative to the other land cover types at all levels of inundation. Agricultural lands occupied the largest portfolio area proportion, 84.4% (123.99 ha), in the 1.5 m

scenario at the \$15M budget level. Agricultural area losses due to inundation ranged from 74.98 ha (0.5 m scenario), or 23.9% of the original 313.36 ha of agricultural lands in the \$10M portfolio, to 398.76 ha (1.5 m scenario), 51.6% of the original 772.84 ha in the \$20M portfolio (Figure 4).

In general, forested upland and developed/barren land together comprised 20% or less of the area of the optimized portfolios. The largest amount of forested upland plus developed/barren land area was 244.76 ha at current MHHW (\$20M), and the smallest area was 17.24 ha at 1.5 m (\$10M). Forested upland area was inundated at similar area increments in the \$10M and \$15M budget scenarios with approximately 50, 21, and 6 ha remaining after the 0.5, 1.0, and 1.5 m sea level rise scenarios, respectively (Figure 4). The proportion of developed/barren land inundated ranged from 13.7% (13.64 ha, \$20M–0.5 m) to 69.6% (37.72 ha, \$15M–1.5 m and 69.50 ha, \$20M–1.5 m; Table 5).

**Figure 4: Area (ha) of land cover types present on optimized parcels under current mean higher high water (MHHW) and three future sea level rise scenarios (0.5 m, 1.0 m, and 1.5 m), grouped by budget scenario.**



**Table 5: Percent of area (ha) inundated relative to current MHHW by land cover type on optimized parcels for three sea level rise scenarios (0.5 m, 1.0 m, and 1.5 m).**

Budget	Sea level rise scenario	Percent (%) of Total Area Inundated				
		Wetland	Forested wetland	Agricultural land	Forested upland	Developed /barren land
\$10M	0.5 m	96.3	36.8	23.9	30.9	14.5
	1.0 m	99.9	90.2	56.2	70.0	25.0
	1.5 m	100.0	99.3	74.5	92.2	37.5
\$15M	0.5 m	95.7	48.4	21.7	32.8	16.8
	1.0 m	99.9	91.4	51.1	71.8	60.0
	1.5 m	100.0	98.1	68.6	92.5	69.6
\$20M	0.5 m	95.1	39.9	16.1	24.0	13.7
	1.0 m	99.7	75.6	37.6	54.1	45.6
	1.5 m	99.9	85.6	51.6	77.2	69.6

Forested wetlands occupied less than 5% of the portfolio area in all budget and sea level rise scenarios. Forested wetland area ranged from 25.89 ha (\$10M) to 67.29 ha (\$20M) during current MHHW, and from 2.54 ha (\$10M) to 16.40 ha (\$20M) during the intermediate 1.0 m rise scenario (Figure 4). The average proportion of forested wetland area inundated across budget scenarios, was 41.7% with a 0.5 m rise in sea level, 85.7% with a 1.0 m rise, and 94.3% with a 1.5 m rise (Table 5).

## DISCUSSION

Binary linear programming optimization outperformed benefit targeting by acquiring a greater conservation benefit across all budget scenarios. Optimization identified the best combination of unprotected tidal marsh parcels that maximized tidal marsh obligate breeding bird density for each budget constraint. At the \$10M level, the optimization model selected a portfolio of 18 parcels with unprotected salt marsh habitat for the protection of existing core tidal marsh bird populations for four species. The model conserved more marsh area (77 ha) and birds (319 tidal marsh obligate birds) than the benefit targeting model by selecting a more efficient combination of parcels and spending approximately \$60,000 more. Furthermore, for benefit targeting to achieve the conservation benefit secured by the optimization model, nearly \$2.9M in supplementary land acquisition funds would be required.

We found similar patterns in the magnitude and direction of the results for the portfolios from the \$15M and \$20M budget level analyses. When the two quantitative methods employed the same budget, optimization secured more birds and marsh area on more parcels than benefit targeting. Similar to the \$10M scenario, an additional \$2.7M and \$1.75M in supplemental funding is needed for benefit targeting to achieve what optimization did with \$15M and \$20M, respectively.

Based on these results and the results of other studies in the literature (Allen et al. 2011, Messer 2006, Messer and Allen 2010), we recommend that federal and state wildlife agencies and non-governmental conservation organizations employ optimization modeling to help evaluate land acquisition projects for wildlife conservation. Our study showed that optimization identified and prioritized a cost-effective set of projects, or parcels, that maximized overall conservation benefits in a quantitative and repeatable manner, while simultaneously allowing conservation planners to objectively make decisions about how to allocate limited funds. While this study evaluated one objective (maximizing bird density), mathematical programming can be used to identify cost-effective projects that meet multiple priority objectives, including competing objectives. Mathematical programming also provides conservation planners with the ability to incorporate important social objectives and constraints into the model,



such as landowners' "willingness to sell" and public support, information which can be obtained from surveys and public voting records. Even though consideration of the human component and its influence on achieving or failing to achieve conservation goals is paramount, most prioritization schemes fail to evaluate social data in the project selection process. Furthermore, sensitivity analyses can be simultaneously produced to help inform management and conservation planning decisions, especially with respect to real or perceived changes in land conservation and preservation budgets.

The application of optimization outside the realm of reserve site selection is growing, and recent literature highlights the innovative use of these algorithms to answer complex avian-specific management and conservation questions. Martin et al. (2007) used the optimal search algorithm Dijkstra to evaluate wintering American redstart (*Setophaga ruticilla*) populations and stable-isotope information. Downs et al. (2008) created a habitat suitability index model to determine nesting site carrying capacity for greater Sandhill cranes (*Grus canadensis tabida*), then modeled carrying capacity using a spatial optimization model (anti-covering problem) to determine the maximum number of pairs an area could support given a home range distance constraint. Stralberg et al. (2009) used a mixed integer programming approach to maximize marsh bird and waterbird abundance by identifying salt ponds for restoration.

In terms of tidal marsh conservation, optimization can be used to define abiotic features and biological community characteristics of target salt marshes to identify critical areas in need of protection that may double as smart investment choices in the face of marsh loss and alteration. Because Delaware is located almost entirely within the Coastal Plain, the state is vulnerable to impacts from global climate change, including projected coastal impacts of accelerated sea-level rise and increased storm frequency, and severity and associated wave velocities. Tidal marsh vulnerabilities to sea level rise were evident in our sea level rise evaluation where over 95% of wetlands on optimization-selected parcels were inundated in all scenarios. Similar projections of inundation hold for saltwater tidal wetlands throughout Delaware; 97% of the state's tidal wetland area will be inundated under 0.5

m of sea level rise and 99% under 1.0 and 1.5 m of sea level rise (Delaware DNREC 2012). However, inundation projections do not equate directly to marsh loss. Some marshes will be able to increase their elevation through natural accretionary processes and keep pace with rising sea levels. Recent models of coastal wetland resilience to sea level rise accounting for ecogeomorphic feedbacks (i.e., inundation, plant growth, organic matter accretion, and sediment deposition) project that marshes with intermediate suspended sediment concentrations will survive conservative sea level rise scenarios, but marshes will likely drown under more rapid accelerations (Kirwan et al. 2010).

Coastal marshes unable to naturally outpace rising seas through sufficient vertical accretion in their current locations will depend on opportunities for marsh migration, transgressing landward and upward over adjoining uplands, to survive (Cahoon et al. 2009). Forests, agricultural lands, and other undeveloped land cover types adjacent to tidal marshes will be necessary to provide opportunities for these wetlands to expand horizontally and migrate inland, given a gradual enough slope and no barriers to migration (e.g., paved surfaces, walls, dikes) (Cahoon et al. 2009). Therefore, information regarding the location of upland areas suitable for marsh migration is central to prepare for and facilitate future tidal marsh conservation.

In our sea level rise assessment of optimization-selected parcels, agricultural land had the greatest amount of area remaining of any land cover type after inundation in all sea level rise scenarios. The initial area of forested upland and developed/barren land was small compared to total wetland and agricultural land area. Portions of forested upland and developed/barren land were inundated in all scenarios, and the total area remaining in the most conservative sea level rise scenario (0.5 m) would support less than a fifth of the original wetland area in the \$10M and \$15M portfolios, and less than a third of the original wetland area in the \$20M portfolio, should marsh migration onto these upland areas be fully realized.

After sea level rise, agricultural lands accounted for at least 70% of the total land area in optimized parcels. If all agricultural land remaining in the \$10M and \$15M portfolios after inundation converted to tidal marsh then

in the 0.5 m sea level rise scenario, approximately 60% of the original wetland area would exist as transgressed tidal marsh. In the \$20M portfolio, converted agricultural lands would sustain 100% of the original wetland area. If sea levels rose 1.5 m by 2100 and all non-inundated agricultural lands converted to marsh, 20% and 25% of the original wetland area would remain in the \$10M and \$15M portfolios, respectively, and 60% of the original wetland area would remain in the \$20M portfolio. Given the results of our sea level rise evaluation, we conclude that when vertical accretion to sustain marsh areas in response to rising seas is not possible, marsh migration onto adjacent agricultural land provides the greatest opportunity for the persistence of tidal marshes and the continued support of core tidal marsh bird populations.

Existing wetland conservation programs on private lands, such as the Wetlands Reserve Program (WRP) and Wildlife Habitat Incentives Program (WHIP), provide landowners with funding for technical and financial support for conservation projects and could provide opportunities for tidal marsh conservation in the future. Both programs are authorized through the U.S. Farm Bill (Food, Conservation, and Energy Act of 2008) and administered by the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS). Through the WRP, landowners protect or enhance wetlands on their property, including restoring wetlands from former agriculture fields, and may be reimbursed up to 100% of conservation easement costs (NRCS 2008). The program is best "suited for frequently flooded agricultural lands, where planned restoration will maximize habitat for migratory birds and other wildlife, and improve water quality" (NRCS undated a). WHIP assists landowners in creating priority fish and wildlife habitat through cost-share agreements, and landowners may be reimbursed up to 90% of the costs (NRCS 2011). While the WRP and WHIP have been successful in creating and conserving habitat in and for the present, more incentives and long-term agreements are needed to bolster private landowners' voluntary program participation to ensure the future existence of habitats and associated species.

Working Lands for Wildlife, a new partnership between NRCS and U.S. Fish and Wildlife Service announced in September 2012, directly addresses conservation for

declining species on working agricultural lands and may be able to provide critical additional support for tidal marsh conservation in the future. The program provides technical and financial assistance through WHIP to farmers, ranchers, and forest owners to reverse declining populations of seven specific wildlife species (i.e., Bog turtle, Gopher tortoise, New England cottontail, Greater sage-grouse, Lesser prairie chicken, Southwestern willow flycatcher, and Golden-winged warbler) (NRCS undated b). Tidal marsh specialist species, such as Saltmarsh Sparrow, should be included in the Working Lands for Wildlife program to encourage conservation efforts in tidal marshes used as working agricultural lands (e.g., salt hay farms) and in other agricultural areas facing saltwater intrusion and encroachment by existing marsh habitat.

Considering predictions for the future of tidal marshes, current avenues for wetland conservation will need to take on new dimensions. A combination of programs like Working Lands for Wildlife and property rights tools such as rolling easements for marsh migration corridors will be needed to achieve conservation goals in the face of global climate change. Regardless of how conservation programs are supported, policies that provide opportunities for wetlands to migrate inland are likely to be less expensive and will have a greater probability of success if planning occurs before these lands are developed (Titus and Neumann 2009).

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