Optimization of Salt Marsh Management at the Edwin B. Forsythe National Wildlife Refuge, New Jersey, Through Use of Structured Decision Making

Open-File Report 2021–1037

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of AT&T marsh at Manahawkin, New Jersey, at the Edwin B. Forsythe National Wildlife Refuge in New Jersey; photograph by the U.S. Fish and Wildlife Service.

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Prepared in cooperation with the U.S. Fish and Wildlife Service

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

FWS	U.S. Fish and Wildlife Service
NWR	national wildlife refuge
NWRS	National Wildlife Refuge System
USGS	U.S. Geological Survey

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Abstract

Structured decision making is a systematic, transparent process for improving the quality of complex decisions by identifying measurable management objectives and feasible management actions; predicting the potential consequences of management actions relative to the stated objectives; and selecting a course of action that maximizes the total benefit achieved and balances tradeoffs among objectives. The U.S. Geological Survey, in cooperation with the U.S. Fish and Wildlife Service, applied an existing, regional framework for structured decision making to develop a prototype tool for optimizing tidal marsh management decisions at the Edwin B. Forsythe National Wildlife Refuge in New Jersey. Refuge biologists, refuge managers, and research scientists identified multiple potential management actions to improve the ecological integrity of 23 marsh management units within the refuge and estimated the outcomes of each action in terms of performance metrics associated with each management objective. Value functions previously developed at the regional level were used to transform metric scores to a common utility scale, and utilities were summed to produce a single score representing the total management benefit that could be accrued from each potential management action. Constrained optimization was used to identify the set of management actions, one per marsh management unit, that could maximize total management benefits at different cost constraints at the refuge scale. Results indicated that, for the objectives and actions considered here, total management benefits may increase consistently up to about $980,000, but that further expenditures may yield diminishing return on investment. Potential management actions in optimal portfolios at total costs less than $980,000 included applying sediment to the marsh surface to increase elevation in five marsh management units, digging runnels on the marsh surface to improve drainage in five marsh management units, and breaching roads and berms to improve tidal flow in five marsh management units. The potential management benefits were derived from expected reduction in the duration of surface flooding, improved capacity for marsh elevation to keep pace with sea-level rise and increases in numbers of spiders (as an indicator of trophic health), tidal marsh obligate birds, and wintering American black ducks. The prototype presented here does not resolve management decisions; rather, it provides a framework for decision making at the Edwin B. Forsythe National Wildlife Refuge that can be updated as new data and information become available. Insights from this process may also be useful to inform future habitat management planning at the refuges.

Introduction

The National Wildlife Refuge System (NWRS) protects extensive salt marsh acreage in the northeastern United States. Much of this habitat has been degraded by a succession of human activities since the time of European settlement (Gedan and others, 2009), and accelerated rates of sea-level rise exacerbate these effects (Gedan and others, 2011; Kirwan and Megonigal, 2013). Therefore, strategies to restore and enhance the ecological integrity of national wildlife refuge (NWR) salt marshes are regularly considered. Management may include such activities as reestablishing natural hydrology, augmenting or excavating sediments to restore marsh elevation, controlling invasive species, planting native vegetation, minimizing shoreline erosion, and remediating contaminant problems. Uncertainty stemming from incomplete knowledge of system status and imperfect understanding of ecosystem dynamics commonly hinders management predictions and consequent selection of the most effective management options. Consequently, tools for identifying appropriate assessment variables and evaluating tradeoffs among management objectives are valuable to inform marsh management decisions.

Structured decision making is a systematic approach to improving the quality of complex decisions that integrates assessment metrics into the decision process (Gregory and

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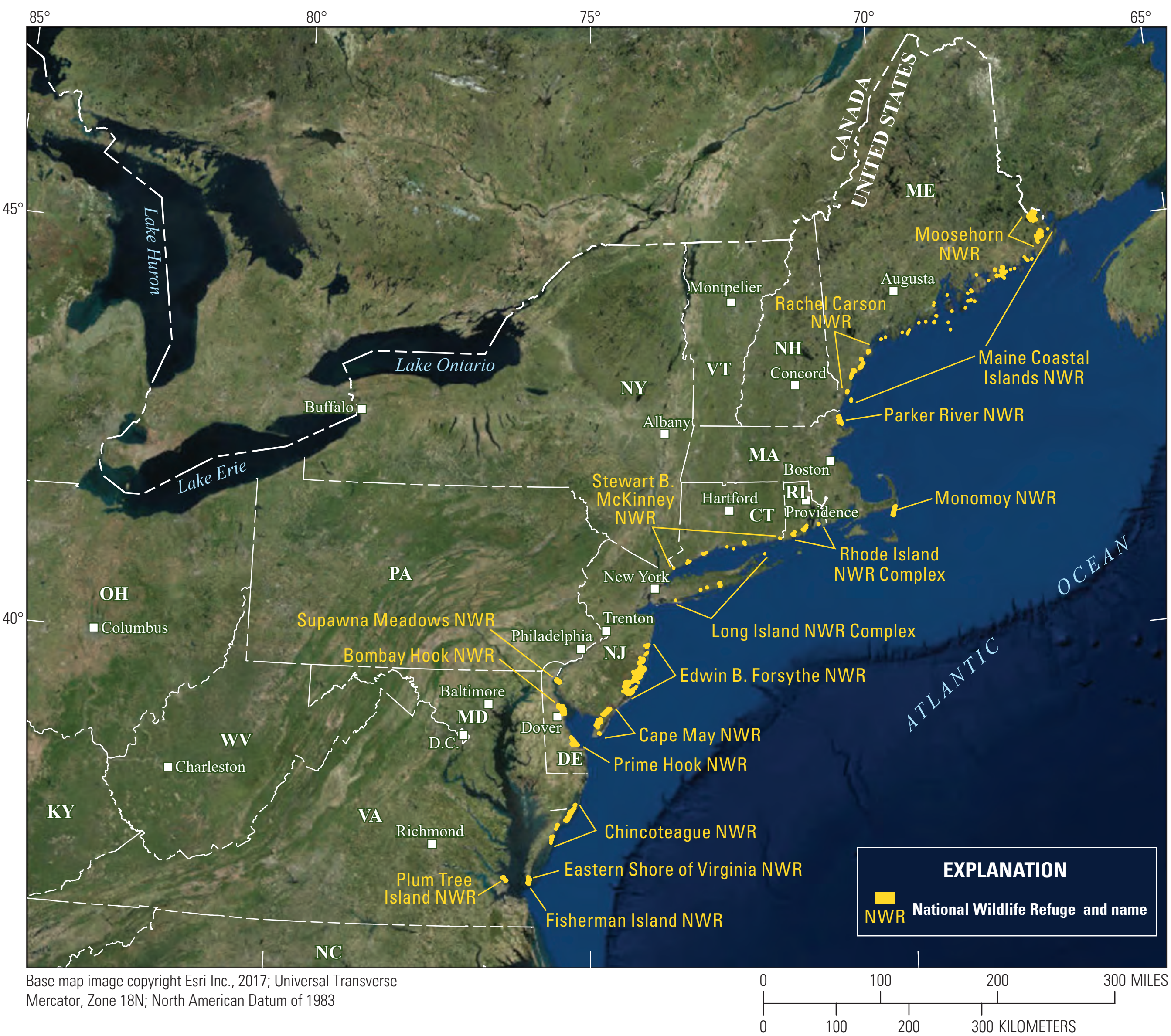
Keeney, 2002). This approach involves identifying measurable management objectives and potential management actions, predicting management outcomes, and evaluating tradeoffs to choose a preferred alternative. From 2008 to 2012, the U.S. Geological Survey (USGS) and U.S. Fish and Wildlife Service (FWS) used structured decision making to develop a framework for optimizing management decisions for NWR salt marshes in the FWS Northeast Region (that is, salt marshes in the coastal region from Maine through Virginia). The structured decision-making steps were applied through successive “rapid prototyping” workshops, an iterative process in which relatively short periods of time are invested to continually improve the decision structure (Blomquist and others, 2010; Garrard and others, 2017). The decision framework includes regional management objectives addressing critical components of salt marsh ecosystems, and associated performance metrics for determining whether objectives are achieved (Neckles and others, 2015). The regional objectives structure served as the foundation for a consistent protocol for monitoring salt marsh integrity at these northeastern coastal refuges, in which the monitoring variables are linked explicitly to management goals (Neckles and others, 2013). From 2012 to 2016, this protocol was used to conduct a baseline assessment of salt marsh integrity at all 17 refuges or refuge complexes in the FWS Northeast Region with salt marsh habitat (fig. 1).

With about 14,000 hectares of salt marsh stretching along more than 80 kilometers of the New Jersey coast (fig. 2), the Edwin B. Forsythe National Wildlife Refuge protects one



Base map image copyright Esri Inc., 2017; Universal Transverse Mercator, Zone 18N; North American Datum of 1983

Figure 1. Map showing national wildlife refuges and national wildlife refuge complexes of the U.S. Fish and Wildlife Service where salt marsh integrity was assessed from 2012 to 2016 using the regional monitoring protocol.

of the largest remaining expanses of salt marsh in the mid-Atlantic region. The refuge's salt marsh provides critical nesting, migratory, and wintering habitat for birds of highest conservation priority, including *Ammodramus caudacutus* (saltmarsh sparrows), *Haematopus palliatus* (American oyster-catchers), *Anas rubripes* (American black ducks), and *Branta bernicla* (Atlantic brant) in the New England and mid-Atlantic coast U.S. North American Bird Conservation Initiative's bird conservation region (FWS, 2004; Steinkamp, 2008; U.S. North American Bird Conservation Initiative, 2020). The primary threats to this habitat are marsh submergence and habitat conversion associated with rising sea level, and, to a lesser degree, shoreline erosion and degradation associated with increasing human activity in the land surrounding the refuge (FWS, 2004, 2013). Salt-marsh management goals set by the FWS for the refuge focus on maintaining high-quality habitat for breeding, migrating, and wintering birds and restoring and enhancing habitat. In this study, the regional structured decision-making framework was used to help prioritize salt marsh management options for the refuge.

Purpose and Scope

This report describes the application of the regional structured decision-making framework (Neckles and others, 2015) to the Edwin B. Forsythe National Wildlife Refuge. The regional framework was parameterized to local conditions through rapid prototyping, producing a decision model for the refuge that can be updated as new information becomes available. Included are a suite of potential management actions to achieve objectives in 23 marsh management units at the refuge (fig. 2), approximate costs for implementing each potential action, predictions for the outcome of each management action relative to individual management objectives, and results of constrained optimization to maximize management benefits subject to cost constraints. This decision structure can be used to understand how specific actions may contribute to achieving management objectives and identify an optimum combination of actions, or "management portfolio," to maximize management benefits at the refuge scale for a range of potential budgets. The prototype presented here provides a framework for continually improving the quality of complex management decisions at the Edwin B. Forsythe National Wildlife Refuge.

Description of Study Area

The Edwin B. Forsythe National Wildlife Refuge is a salt marsh dominated system located in southern New Jersey along the Atlantic Ocean. The refuge's salt marsh spans several estuaries and is divided into 23 marsh management units. The majority of the marsh units border coastal lagoon-type estuaries (including Barnegat Bay, Little Egg Harbor, and Metedeconk River) that have small tidal ranges and limited ocean water exchange. The southernmost marsh units border a drowned river estuary system (Great Bay) with greater tidal ranges and ocean water exchange than found in the north. Most of the marsh management units have been ditched extensively for mosquito control; however, two units (Motts-Mullica Wilderness and Little Beach-Holgate; fig. 2*D*) lie within a federally-designated wilderness area (FWS, 2004) and protect about 2,200 hectares of unditched salt marsh. Human population growth in the region has spurred construction of housing and supporting infrastructure on property outside the refuge; much of the area between the boundaries of the marsh management units and a 1,000-meter buffer consists of developed land, as classified within the 2011 National Land Cover Database (Multi-Resolution Land Characteristics Consortium, 2020; S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017). The marsh management units are generally well-flushed with estuarine water. The invasive plant *Phragmites australis* (hereafter referred to as *Phragmites*) consistently occurs in the transition zone between upland forest and salt marsh and sporadically on high elevation sites throughout the refuge's salt marsh habitat. During 2012–14, average salt marsh surface-water salinities in the summer ranged from about 10 to about 30 parts per thousand (ppt; mesohaline to euhaline as defined by Cowardin and others, 1979) within the marsh management units (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017).

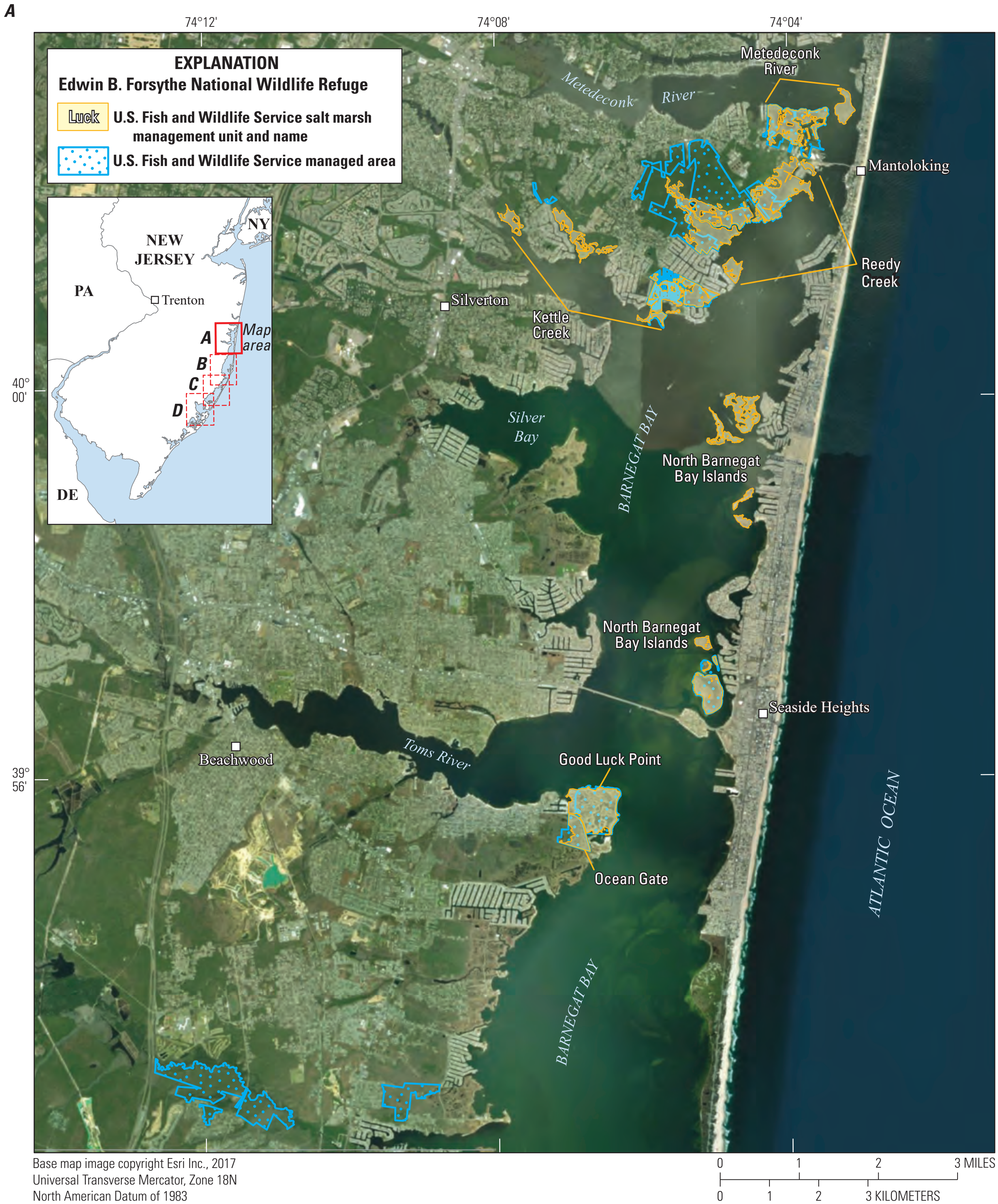
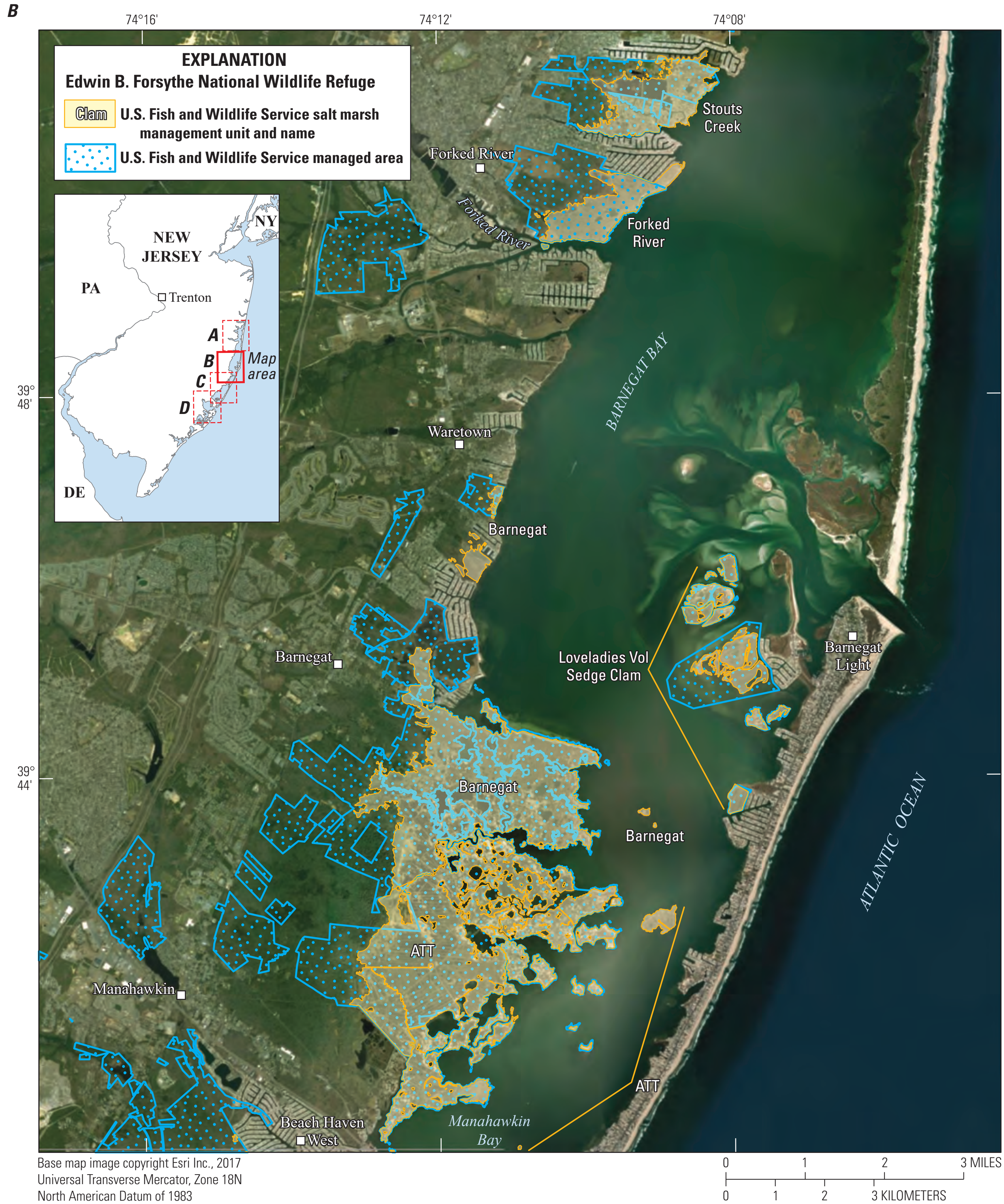


Figure 2. Map showing marsh management units at the *A*, northern, *B*, north central, *C*, south central, and *D*, southern parts of the Edwin B. Forsythe National Wildlife Refuge in New Jersey. U.S. Fish and Wildlife Service managed areas shown for reference.

B



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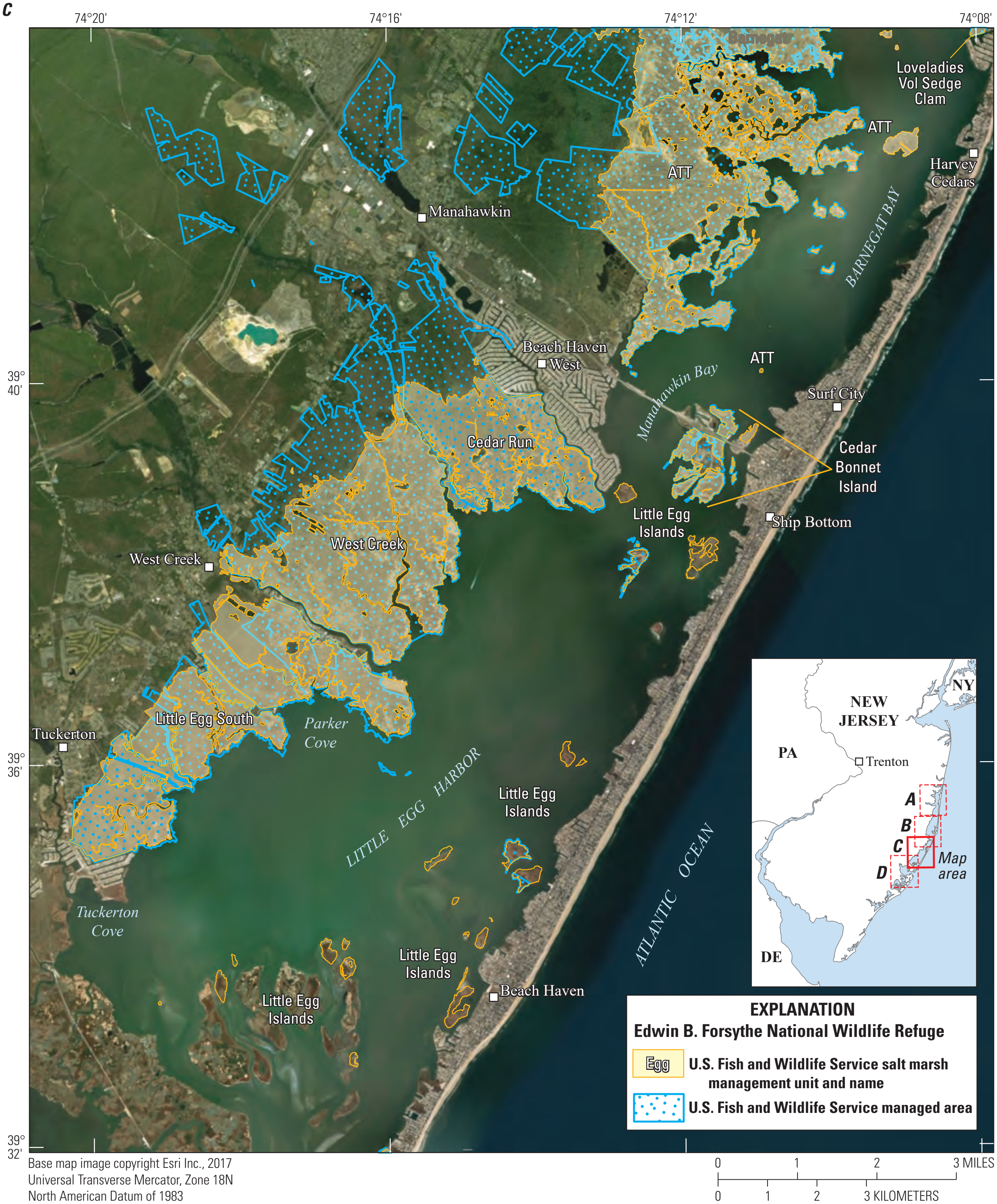
C



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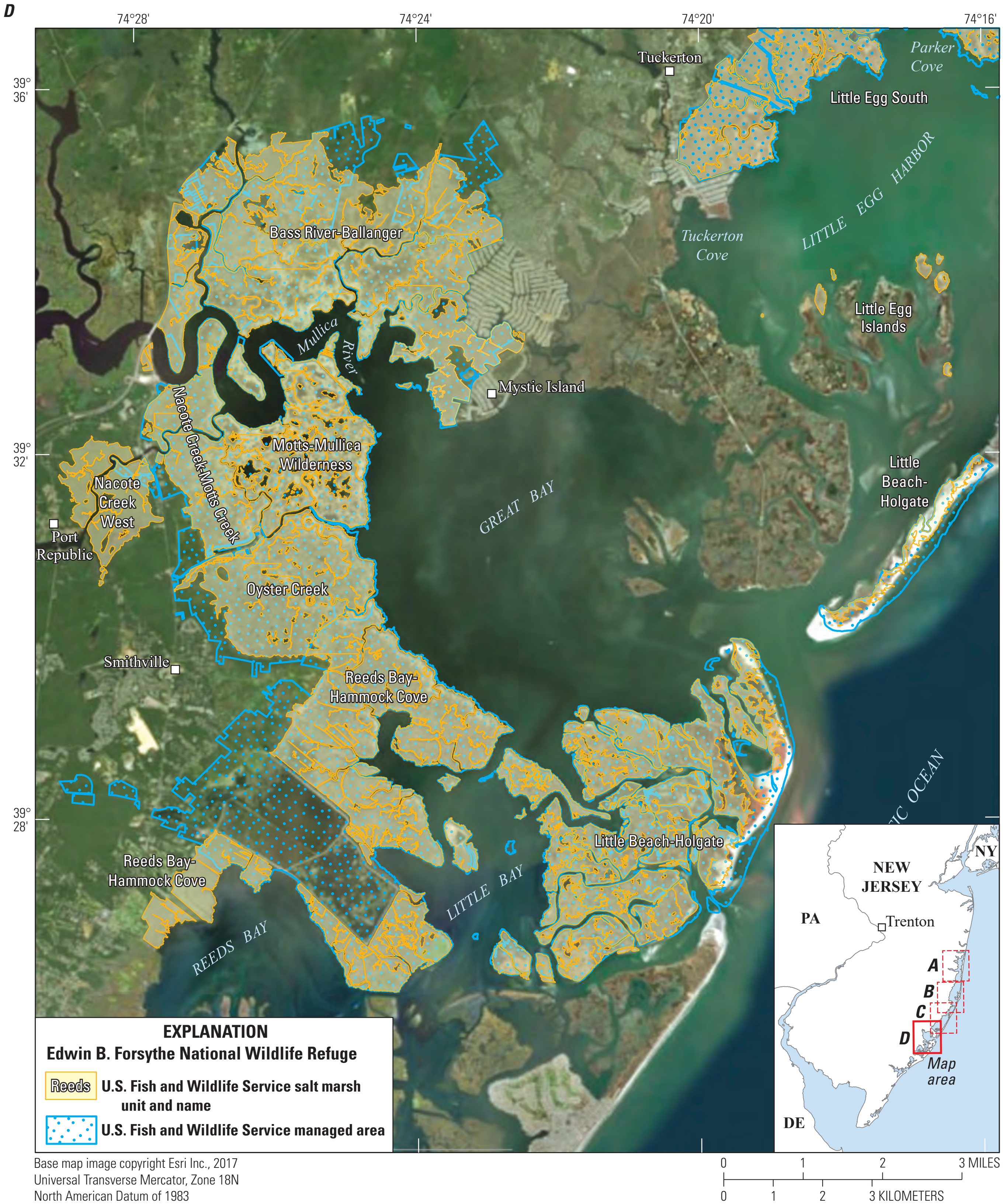

Figure 2. Map showing marsh management units at the A, northern, B, north central, C, south central, and D, southern parts of the Edwin B. Forsythe National Wildlife Refuge in New Jersey. U.S. Fish and Wildlife Service managed areas shown for reference.—Continued

Regional Structured Decision-Making Framework

A regional framework for assessing and managing salt marsh integrity at northeastern NWRs was developed through collaborative efforts of FWS regional and refuge managers and biologists, salt marsh research scientists, and structured decision-making experts. This process followed the discrete steps outlined by Hammond and others (1999) and Gregory and Keeney (2002):

1. Clarify the temporal and spatial scope of the management decision.

2. Define objectives and performance measures to evaluate whether objectives are achieved.

3. Develop alternative management actions for achieving objectives.

4. Estimate the consequences or likely outcomes of management actions in terms of the performance measures.

5. Evaluate the tradeoffs inherent in potential alternatives and select the optimum alternatives to maximize management benefits.

This sequence of steps was applied through successive workshops to refine the decision structure and incorporate newly available information. Initial development of the structured decision-making framework occurred during a week-long workshop in 2008 to define the decision problem, specify management objectives, and explore potential strategies available to restore and enhance salt marsh integrity. During 2008 and 2009, workshop results were used to guide field tests of salt marsh monitoring variables (Neckles and others, 2013). Subsequently, in 2012, data and insights gained from these field tests were used in a two-part workshop to refine management objectives and develop the means for evaluating management outcomes (Neckles and others, 2015).

From the outset, FWS goals included development of an approach for consistent assessment of salt marsh integrity across all northeastern NWRs (fig. 1). Within this regional context, staff at a given refuge must periodically determine the best approaches for managing salt marshes to maximize habitat value while considering financial and other constraints. The salt marsh decision problem was thus defined as applying to individual NWRs over a 5-year planning horizon. The objectives for complex decisions can be organized into a hierarchy to help clarify what is most important to decision makers (Gregory and others, 2012). The hierarchy of objectives for salt marsh management decisions (table 1) was based explicitly on the conservation mission of the NWRS, which is upheld through FWS management to “ensure that the biological integrity, diversity, and environmental health of the System are maintained for the benefit of present and future generations of Americans,” as mandated in the National Wildlife Refuge System Improvement Act of 1997 (16 U.S.C. §668dd note). Two fundamental objectives, or the overall goals for salt marsh management decisions, were drawn from this policy to maximize (1) biological integrity and diversity, and (2) environmental health, of salt marsh ecosystems. Participants in the prototyping workshops deconstructed these overall goals further into lower level objectives relating to salt marsh structure and function and identified performance metrics to evaluate whether objectives are achieved (table 1). In addition, performance metrics were weighted to reflect the relative importance of each objective (Neckles and others, 2015).

The hierarchy of objectives for salt marsh management (table 1) provides the foundation for identifying possible management actions at individual NWRs and predicting management outcomes. Workshop participants developed preliminary influence diagrams (app. 1), or conceptual models relating management actions to responses by each performance metric (Conroy and Peterson, 2013), to guide this process. To allow metric responses to be aggregated into a single, overall performance score, participants also defined value functions relating salt marsh integrity metric scores to perceived management benefit on a common, unitless “utility” scale (Keeney and Raiffa, 1993). Stakeholder elicitation was used to determine the form of each value function relating the original metric scale to the utility scale, ranging from 0, representing the lowest management benefit, to 1, representing the highest benefit (app. 2). Neckles and others (2015) provided details regarding development of the structured decision-making framework and a case-study application to Prime Hook National Wildlife Refuge in Delaware.

Table 1. Objectives hierarchy for salt marsh management decision problems.

[Two fundamental objectives (overall goals of the decision problem) draw directly from U.S. Fish and Wildlife Service (FWS) National Wildlife Refuge System policy to maintain, restore, and enhance biological integrity, diversity, and environmental health within the refuge. These are broken down into lower level objectives focused on specific aspects of marsh structure and function. Values in parentheses are weights assigned to objectives, reflecting their relative importance. Weights on any branch of the hierarchy (that is, objectives that are at the same level of the hierarchy under a fundamental objective) sum to one. The weight for each metric is the product of the weights from each level of the hierarchy leading to that metric]

FWS objectives	Performance metrics	Unit of measurement
	Maximize biological integrity and diversity[1] (0.5)	
Maximize cover of native vegetation (0.24)	Cover of native vegetation	Percent
Maximize abundance and diversity of native nekton (0.18):		
Maximize nekton abundance (0.50)	Native nekton density	Number per square meter
Maximize nekton diversity (0.50)	Native nekton species richness	Number of native species
Maintain sustainable populations of obligate salt marsh breeding birds (0.20)	Abundance of four species of tidal marsh obligate birds (clapper rail, willet, saltmarsh sparrow, seaside sparrow)	Number per marsh management unit from call-broadcast surveys, summed across all sampling points in unit
Maximize use by nonbreeding wetland birds (0.20)	Abundance of American black duck as indicator species	Relative abundance for refuge during wintering waterfowl season (low, medium, high)[2]
Maintain trophic structure (0.18)	Density of spiders as indicator taxon	Number per square meter
	Maximize environmental health[1] (0.5)	
Maintain natural hydrology (0.44):		
Maintain natural flooding regime (0.50)	Percent of time marsh surface is flooded relative to ideal reference system	Absolute deviation from reference in percentage points
Maintain natural salinity (0.50)	Surface-water salinity relative to ideal reference system	Absolute deviation from reference in parts per thousand
Maintain the extent of the marsh platform (0.44)	Change in marsh surface elevation relative to sea-level rise	0=change in elevation is less than amount of sea-level rise; 1=change in elevation greater than or equal to amount of sea-level rise
Minimize use of herbicides (0.12)	Rate of application	0=no herbicide applied; 1=herbicide applied

[1]Fundamental objectives of salt marsh management decisions.

[2]Relative abundance based on local knowledge.

Application to the Edwin B. Forsythe National Wildlife Refuge

In November 2016, FWS regional biologists, biologists and managers from six northeastern NWR administrative units, and USGS and University of Delaware research scientists (table 2) participated in a 1.5-day rapid-prototyping workshop to apply the regional structured decision-making framework to the Chincoteague, Bombay Hook, Cape May, Supawna Meadows, and Forsythe National Wildlife Refuges and the Rhode Island National Wildlife Refuge Complex. Participants worked within refuge-specific small groups to focus on management issues at individual refuges. Plenary discussions of common patterns of salt marsh degradation, potential management strategies, and mechanisms of ecosystem response offered additional insights to enhance refuge-specific discussions.

Participants identified a range of possible management actions for achieving objectives within each marsh management unit at the Edwin B. Forsythe National Wildlife Refuge and estimated the total cost of implementation over a 5-year period; the specific years of implementation were not identified in this prototype. Potential actions to enhance salt marsh integrity included restoring natural hydrology, controlling *Phragmites*, protecting shorelines, or altering marsh elevation or vegetation succession (table 3, in back of report). Participants predicted the outcomes of each management action 5 years after initial implementation in terms of salt marsh integrity performance metrics. For most metrics, baseline conditions within each unit measured during the 2012–16 salt marsh integrity assessment (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017) were used to predict the outcomes of a “no-action” alternative. Baseline conditions were estimated by using expert judgement for three metrics that lacked assessment data (abundance of American black ducks, density of spiders, change in marsh surface elevation relative to sea-level rise). Regional influence diagrams relating management strategies to outcomes aided in predicting consequences of management actions (app. 1). Although the influence diagrams incorporated the potential effects of stochastic processes, including weather, sea-level rise, herbivory, contaminant inputs, and disease, on management outcomes, no attempt was made to quantify these sources of uncertainty during rapid prototyping. Management predictions also inherently included considerable uncertainty surrounding the complex interactions among controlling factors and salt marsh ecosystem components.

Following the workshop, the potential management benefit of each salt marsh integrity performance metric was calculated by converting salt marsh integrity metric scores (table 3, workshop output) to weighted utilities (table 4, in back of report), using regional value functions (app. 2). Weighted utilities were summed across all salt marsh integrity metrics for each action; this overall utility therefore represented the total management benefit, across all objectives, expected to accrue from a given management action (table 4). Constrained optimization (Conroy and Peterson, 2013) was used to find the management portfolio (the combination of actions, one action per marsh management unit) that maximizes the total management benefit across all units under varying cost scenarios for the entire the refuge. Constrained optimization using integer linear programming was implemented in the Solver tool in Microsoft Excel (Kirkwood, 1997). Budget constraints were increased in $5,000 increments up to $50,000; in $50,000 increments up to $200,000; in $100,000 increments up to $1 million; in $500,000 increments up to $2.5 million; and in $5 million increments thereafter. The upper limit to potential costs was not determined in advance; rather, it reflected the total estimated costs of the proposed management actions. A cost-benefit plot of the portfolios identified through the optimization analysis was used to identify the efficient frontier for resource allocation (Keeney and Raiffa, 1993), which is the set of portfolios that are not dominated by other portfolios at similar costs (or the set of portfolios with maximum total benefit for a similar cost). The cost-benefit plot also revealed the

Table 2. Participants in the workshop convened at the Edwin B. Forsythe National Wildlife Refuge, New Jersey, to apply a regional framework for optimizing salt marsh management decisions to five national wildlife refuges in November 2016.

[FWS, U.S. Fish and Wildlife Service; NWR, National Wildlife Refuge; USGS, U.S. Geological Survey]

Affiliation	Participant
FWS NWR specialists	
Bombay Hook NWR	Susan Guiteras
Cape May NWR and Supawna Meadows NWR	Brian Braudis
Cape May NWR and Supawna Meadows NWR	Heidi Hanlon
Cape May NWR and Supawna Meadows NWR	Victor Nage
Cape May NWR and Supawna Meadows NWR	Jack Szczepanski
Chincoteague NWR	Kevin Holcomb
Chincoteague NWR	Jennifer Miller
Edwin B. Forsythe NWR	Paul Castelli
Edwin B. Forsythe NWR	Virginia Rettig
Rhode Island NWR Complex	Nick Ernst
Rhode Island NWR Complex	Charlie Vandemoer
FWS regional experts	
Northeast Regional Office	Laura Mitchell
Rachel Carson NWR	Susan Adamowicz
Rachel Carson NWR	Toni Mikula
Research scientists	
University of Delaware	W. Gregory Shriver
USGS Eastern Ecological Science Center	Glenn Guntenspergen
USGS Eastern Ecological Science Center	James Lyons
USGS Eastern Ecological Science Center	Hilary Neckles

cost above which further expenditures would yield diminishing returns on investment. To exemplify use of the decision-making framework to understand how a given portfolio could affect specific management objectives, the refuge-scale management benefits for individual performance metrics were compared between one optimal portfolio and those predicted with no management action taken.

Results of Constrained Optimization

Potential management actions identified to improve marsh integrity at the Edwin B. Forsythe National Wildlife Refuge included adding sediment to the marsh surface to increase elevation; establishing living shorelines (plants or other natural elements for shoreline stabilization) to help protect the salt marsh edge from erosion; restoring natural hydrology through breaching berms and digging shallow runnels on the marsh surface; and spraying herbicide to control *Phragmites* (table 3). For costs ranging from $0 to $16.5 million, the estimated management benefits for individual actions across all metrics, measured as weighted utilities, ranged from 0.399 (for implementing no action in the Kettle Creek marsh management unit) to 0.976 (for restoring open-water salt hay farms to marsh in the Cedar Run marsh management unit), out of a maximum possible total management benefit of 1.0 (tables 3 and 4). In each marsh management unit, the alternative with both the lowest management benefit and lowest cost was generally the “no action” alternative (action A); however, for Stouts Creek, Barnegat, and Forked River marsh management units, actions to breach berms for improving tidal flow would be accomplished through a partner contribution, and thus also had no associated cost. In addition, in many marsh management units, controlling *Phragmites* through herbicide use yielded a lower total management benefit than implementing no management actions.

Constrained optimization was applied to identify the optimal management portfolios over 5 years for a range of total costs to the refuge. As total cost increased from $0 (no action in most units) to about $9.65 million, the total management benefit at the refuge scale increased from 15.483 to 19.345 (a 25-percent increase; table 5), out of a possible maximum of 23.0 (the maximum possible total management benefit of 1.0 for any management action, summed across 23 marsh management units). Graphical analysis showed a fairly consistent increase in management benefit as costs increased to about $982,000 (fig. 3, portfolio 13). Portfolio 13 represented a turning point in the cost-benefit plot. As expenditures increased beyond the cost of portfolio 13, total management benefit continued to increase but at a lower rate, yielding diminishing returns on investment; there was very little gain in management benefit for expenditures greater than about $2 million (fig. 3, portfolio 15).

Several patterns emerged relative to the potential management actions selected by constrained optimization within the set of portfolios that yielded the greatest total management benefit per unit cost (table 5, portfolios 2 through 13). Actions that could enhance or restore marsh hydrology, including digging runnels or breaching berms to improve tidal flow, were always included in the optimal portfolios (involving ATT, West Creek, Oceangate, North Barnegat Bay Islands, Good Luck Point, Stouts Creek, Barnegat, Cedar Bonnet Island, Little Egg South, Forked River, and Cedar Run marsh management units). At five marsh management units (Loveladies Vol Sedge Clam, Metedeconk River, Reedy Creek, Kettle Creek, and Little Egg Islands), sediment enrichment was the primary management action included in portfolios 2 through 13, whereas at six units (Oyster Creek, Motts-Mullica Wilderness, Bass River-Ballanger, Nacote Creek-Motts Creek, Nacote Creek West, and Reeds Bay-Hammock Cove), the no-action alternative was selected consistently. In contrast, other management actions were never or rarely included in an optimal portfolio at a cost of less than $1 million. Although installation of living shorelines was identified to reduce marsh-edge erosion for most marsh management units, this action was rarely selected; living shorelines were never included in optimal portfolios costing less than $1 million, and were included in more costly portfolios for four units only (Bass River-Ballinger, Nacote Creek-Motts Creek, Nacote Creek West, and Reeds Bay-Hammock Cove marsh management units). Similarly, spraying herbicide to control *Phragmites* was identified to improve integrity of many marsh management units, but this action was never selected during constrained optimization.

Examination of the refuge-scale metric responses to actions included in portfolio 13, which is the turning point in the cost-benefit plot (fig. 3), revealed how implementation could affect specific management objectives. The actions included in portfolio 13 were predicted to achieve large gains in the overall management benefits derived from increased density of spiders (as an indicator of trophic health), reduced duration of flooding, and the capacity of marsh elevation to keep pace with sea-level rise, and modest gains in the benefits derived from changes to the nekton density, numbers of tidal marsh obligate birds, and American black ducks in winter (fig. 4). Ecologically, the combination of actions in this portfolio predicted an average 213-percent increase in tidal marsh obligate bird counts (averaged across all marsh management units), 465-percent increase in spider density, 52-percent increase in nekton density, and 35-percent decrease in the deviation of surface flooding from the ideal reference condition (derived as the average difference between the predicted metric scores for the actions implemented in portfolio 13 and the “no-action” alternative; table 3). Implementation of actions in this portfolio was predicted also to improve the capacity for marsh elevation to keep pace with sea-level rise in 5 of the 23 marsh management units. The management benefits predicted for portfolios 1 through 12, at total costs up to about $886,000, were derived primarily from expected improvements in surface-water drainage and consequent flooding duration, and presumed increases in densities of spiders, numbers of tidal marsh obligate birds, and capacity for marsh elevation to keep pace with sea-level rise (tables 3 and 4).

Table 5. Actions included in various management portfolios to maximize the total management benefits subject to increasing cost constraints at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.

[Letter designations for actions refer to specific actions and are listed in tables 3 and 4. Portfolios represent the combination of potential actions, one per marsh management unit, that maximized the total management benefit across all units, subject to a refuge-wide cost constraint. The management actions constituting individual portfolios were selected using constrained optimization. The maximum possible total management benefit for the refuge is 23, derived as the maximum possible total management benefit of 1.0 for any management action within one management unit, summed across 23 units.]

Portfolio	Marsh management unit																							Total cost (dollars)	Total management benefit
	Loveladies Vol Sedge Clam	ATT	West Creek	Ocean gate	Metedeconk River	Reedy Creek	Kettle Creek	North Barnegat Bay Islands	Good Luck Point	Stouts Creek	Barnegat	Cedar Bonnet Island	Little Egg South	Oyster Creek	Little Egg Islands	Motts-Mullica Wilderness	Bass River-Ballanger	Forked River	Little Beach-Holgate	Cedar Run	Nacote Creek-Motts Creek	Nacote Creek West	Reeds Bay-Hammock Cove		
1	A	A	A	A	A	A	A	A	A	B	B	A	A	A	A	A	A	B	A	A	A	A	A	0	15.483
2	A	C	A	F	A	A	A	D	C	B	B	A	B	A	A	A	A	B	A	A	A	A	A	5,000	16.531
3	A	C	E	F	A	A	A	D	C	B	B	A	B	A	A	A	A	B	B	A	A	A	A	8,500	16.959
4	A	C	E	F	A	A	A	D	C	B	B	A	B	A	A	A	A	B	B	B	A	A	A	28,500	16.979
5	A	C	E	F	A	A	B	D	C	B	B	A	B	A	A	A	A	B	B	A	A	A	A	138,400	17.334
6	B	C	E	F	A	A	B	D	C	B	B	A	B	A	A	A	A	C	B	B	A	A	A	294,400	17.724
7	B	C	E	F	A	A	B	B	C	B	B	A	B	A	A	A	A	C	B	B	A	A	A	400,000	17.729
8	D	C	E	F	A	B	B	D	C	B	B	A	B	A	A	A	A	C	B	B	A	A	A	460,600	17.975
9	D	C	E	F	B	B	B	D	C	B	B	A	B	A	A	A	A	B	B	B	A	A	A	596,600	18.168
10	G	C	E	F	B	B	B	D	C	B	B	A	B	A	C	A	A	B	B	A	A	A	A	694,600	18.278
11	D	C	E	F	B	B	B	D	C	B	B	A	B	A	C	A	A	C	B	B	A	A	A	731,600	18.298
12	D	E	E	F	B	B	B	D	C	B	B	C	B	A	A	A	A	B	B	B	A	A	A	885,600	18.414
13	D	C	E	F	B	B	B	D	C	B	B	C	B	A	C	A	A	C	B	B	A	A	A	981,600	18.544
14	D	C	E	F	B	B	B	B	C	B	B	C	B	A	C	A	A	B	B	B	D	A	A	1,481,200	18.792
15	G	C	C	F	B	B	B	D	C	B	B	C	B	A	C	B	A	C	B	D	D	A	A	1,996,300	18.967
16	D	C	C	C	B	B	B	B	C	B	B	C	C	A	C	B	A	C	B	D	D	A	A	2,480,500	19.05
17	D	F	C	E	B	B	B	B	C	B	C	C	C	A	C	B	A	B	B	D	D	B	A	4,296,000	19.122
18	D	F	C	E	B	B	B	B	C	B	C	C	C	A	C	B	A	C	B	D	D	A	B	7,184,500	19.342
19	B	F	C	E	B	B	B	B	C	B	C	C	C	A	C	B	C	C	B	D	D	B	B	9,649,500	19.345

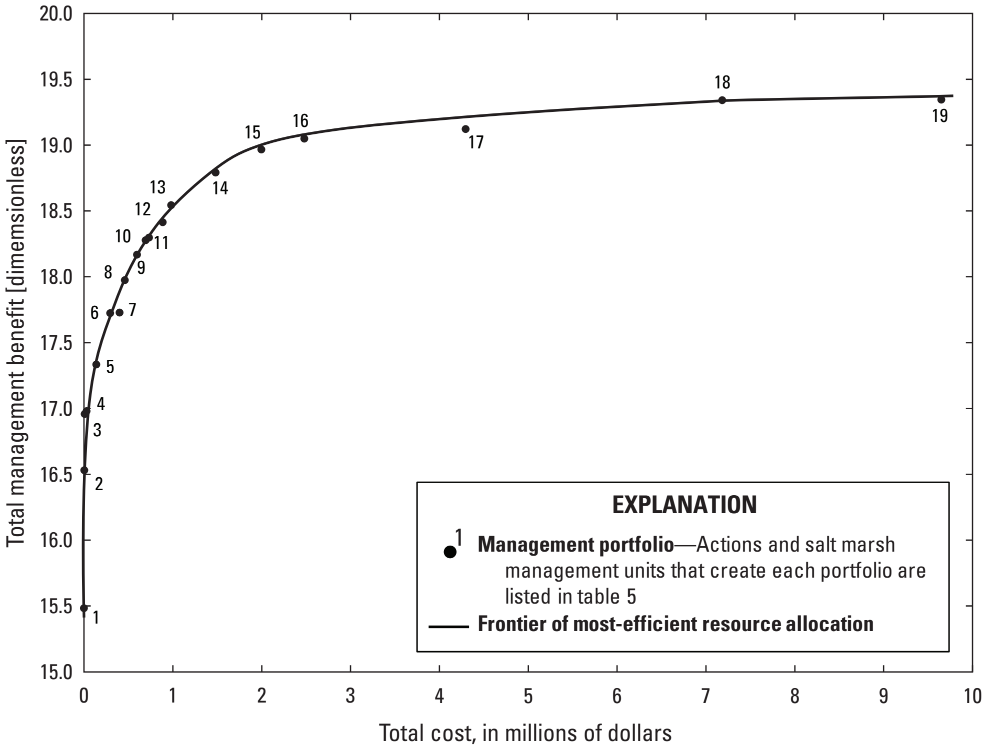

Figure 3. Graph showing predicted total management benefit of various portfolios, expressed as weighted utilities, relative to total cost at the Edwin B. Forsythe National Wildlife Refuge in New Jersey. Each portfolio (dot with number) represents a combination of 23 management actions, one per marsh management unit, as identified in table 5. The line represents the efficient frontier for resource allocation.

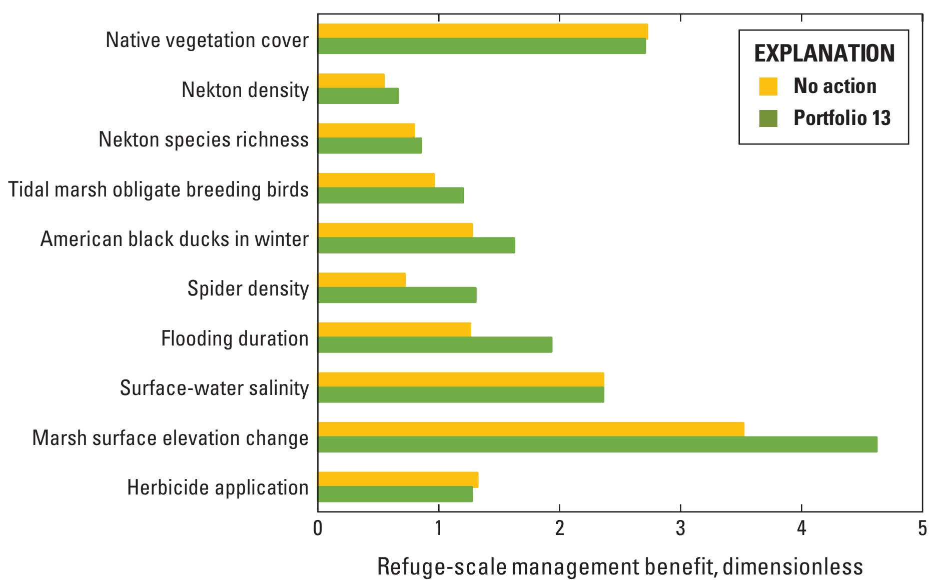

Figure 4. Predicted management benefit at the refuge scale for individual performance metrics, expressed as weighted utilities, resulting from implementation of the management actions included in portfolio 13, in comparison to the management benefit from the baseline "no-action" portfolio, at the Edwin B. Forsythe National Wildlife Refuge in New Jersey. The actions included in each portfolio are listed in table 5.

Considerations for Optimizing Salt Marsh Management

A regional structured decision-making framework for salt marshes on NWRs in the northeastern United States was applied by the USGS, in cooperation with the FWS, to develop a tool for optimizing management decisions at the Edwin B. Forsythe National Wildlife Refuge. Use of the existing regional framework and a rapid-prototyping approach permitted NWR biologists and managers, FWS regional authorities, and research scientists to construct a decision model for the refuge within the confines of a 1.5-day workshop. This preliminary prototype provides a local framework for decision making while revealing information needs for future iterations. Insights from this process may also be useful to inform future habitat management planning at the refuge.

The suite of potential management actions and predicted outcomes included in this prototype (table 3) were based on current understanding of the Edwin B. Forsythe National Wildlife Refuge salt marshes and hypothesized process-response pathways (app. 1). Multiple, interacting factors influence the long-term success of restoration actions in prolonging marsh integrity and improving marsh resilience (Roman, 2017). Tidal flooding is the predominant physical control on the structure and function of salt marsh ecosystems (Pennings and Bertness, 2001), and there is widespread scientific effort to elucidate how salt marshes may respond to accelerating rates of sea-level rise and management strategies to enhance their sustainability (Kirwan and Megonigal, 2013; Roman, 2017). Thin-layer deposition of sediments to raise marsh elevation and excavation of runnels, or shallow creeks, to improve surface drainage are increasingly proposed to enhance sustainability of northeastern salt marshes threatened with submergence, although responses to these management actions may depend on many site-specific factors (Wigand and others, 2017). In this prototype, the high management benefit predicted to accrue from sediment enhancement and runnel creation led to the frequent selection of these actions within optimal portfolios. However, in a Rhode Island study, excavation of runnels to partially drain ponded water from salt marsh surfaces assisted in maintaining cover by high-marsh vegetation (*Spartina patens*), whereas sediment enhancement did not (Perry, 2020). Ultimately, the conversion of uplands to wetlands driven by sea-level rise may be the most important determinant of future marsh area. In the absence of anthropogenic barriers to marsh migration, land conversion is controlled by the slope and cover of coastal uplands; the stresses to upland vegetation caused by salinity and inundation; and synergistic disturbance events such as storms and insect outbreaks (Kirwan and Gedan, 2019). In Delaware Bay, *Phragmites* frequently invades the zone of retreating forest, forming a fringing band at the salt marsh-forest ecotone that can impede inland salt marsh migration (Smith 2013). In this prototype, removing dead trees and killing *Phragmites* was hypothesized as a possible management action to facilitate marsh migration in eight marsh management units (table 3), but there was little information available to inform the predicted consequences. Future iterations of this decision model can incorporate improved understanding of the potential for marsh migration and processes controlling marsh responses to management actions. In addition, during construction of the regional decision model, a lack of widely available data on rates of vertical marsh growth led to the adoption of a very coarse scale of measurement for change in marsh surface elevation relative to sea-level rise (table 1). In 2014, surface elevation tables (Lynch and others, 2015) were installed in 14 marsh management units to obtain high-resolution measurements of change in marsh surface elevation (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017). Incorporating this information into subsequent iterations of this structured decision-making framework would likely improve predictions related to the potential for marsh surface elevation to keep pace with sea-level rise.

Results of constrained optimizations (table 5) based on the objectives, management actions, and predicted outcomes included in this prototype identified four major areas in which to improve the utility of the prototype for decision making at the Edwin B. Forsythe National Wildlife Refuge. First, although loss of marsh area through shoreline erosion is a concern in some areas within the marsh complex, reducing wave action through the construction of living shorelines was generally excluded from optimal portfolios. Living shorelines may not be a practical management option at this refuge. Additionally, deconstructing the objective of maintaining the extent of the marsh platform into subordinate objectives and performance metrics related to both horizontal and vertical gains and losses may help focus decision making on the various drivers of marsh area. Second, the transparency of the structured decision-making framework reveals the tradeoffs associated with using herbicide to control *Phragmites*; the predicted increases in management benefit associated with various aspects of marsh structure and function did not outweigh the predicted decrease in management benefit associated with chemical application (table 4). Where spread of *Phragmites* is a management concern at the Edwin B. Forsythe National Wildlife Refuge, this prototype could be adapted to allow managers to evaluate the relative expected benefits and detriments of chemical and other control methods. These results emphasize the importance that refuge managers have already placed on considering methods in addition to herbicides, including prescribed burning, biological control, and hydrologic restoration, to control *Phragmites* through an integrated approach (FWS, 2013). Third, there were multiple marsh management units for which the no-action alternative was selected for the optimal portfolios at either all or nearly all of the total cost constraints (table 5). Rapid prototyping did not allow in-depth analysis of the causes of marsh degradation and potential management actions in all 23 marsh management units, and managers may want to explore additional methods for improving marsh integrity in some units. Recent research has synthesized multiple spatial datasets from Edwin B. Forsythe

National Wildlife Refuge to locate the marsh areas that are most vulnerable to degradation (Defne and others, 2020), and Neeson and others (2016) showed that the cost of restoration in general may be lower at sites with a small number of severe problems than at sites with more numerous but less severe problems. This type of information could be used to prioritize investments among the marsh management units in planning, applications of the decision model, and assessments. Finally, the constrained optimizations analyzed in this report were based on approximations of management costs. As salt marsh management is undertaken around the region, a detailed list of actual expenses can be compiled, including staff time for project planning as well as materials, equipment, contracts, and staff time for implementation. This will allow future iterations of the decision model to include more accurate cost estimates.

The prototype model for the Edwin B. Forsythe National Wildlife Refuge provides a useful tool for decision making that can be updated in the future with new data and information. The spatial and temporal variability inherent in parameter estimates were not quantified during rapid prototyping. Previously, preliminary sensitivity analysis revealed little effect of incorporating ecological variation in abundance of marsh-obligate breeding birds on the optimal solutions for Prime Hook National Wildlife Refuge (Neckles and others, 2015). This lends confidence to use of this framework for decision making; however, including probability distributions for each performance metric in the decision model could be a high priority for future prototypes. Future monitoring of salt marsh integrity performance metrics will be useful to refine baseline parameter estimates and to determine the background rate of change in the absence of management actions, and feedback from measured responses to management actions around the region will help reduce uncertainties surrounding management predictions. The structured decision-making framework applied here to the Edwin B. Forsythe National Wildlife Refuge is based on a hierarchy of regional objectives and regional value functions relating performance metrics to perceived management benefits. It will be important to ensure that subsequent iterations reflect evolving management objectives and desired outcomes. Elements of the decision model could be further adapted, for example through differential weighting of objectives or altered value functions, to reflect specific, local management goals and mandates. Future optimization analyses that use this framework could also incorporate additional constraints on action selection, such as ensuring that particular actions within individual marsh management units are included in optimal management portfolios, to further tailor the model to refuge-specific needs.

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Table 3. Possible management actions for achieving objectives within marsh management units at the Edwin B. Forsythe National Wildlife Refuge in New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.

[%, percent; ppt, parts per thousand]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton density (number of animals per square meter)	Nekton species richness (number)	Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Duration of surface flooding[2]	Surface-water salinity[2] (ppt)	Marsh surface elevation change relative to sea-level rise[3]	Herbicide application (pints per year)
Loveladies Vol Sedge Clam											
A. No action	0	100	19.3	9	1.97	Medium	1	30	11	0	0
B. Sediment deposition of dredge materials on Clam Island to increase elevation and enlarge marsh area	135,000	90	30	9	4	High	15	11	11	1	1
C. Living shoreline along southwest edge of Clam Island	750,000	90	19	9	2	Medium	1	30	11	0	0
D. Sediment deposition of dredge materials on High Bar Island to increase elevation and enlarge marsh area	145,000	90	30	9	4	High	15	11	11	1	1
E. Living shoreline along southwest edge of High Bar Island	1,012,500	90	19	9	2	Medium	1	30	11	0	0
F. Living shoreline at Vol Sedge	562,500	90	19	9	2	Medium	1	30	11	1	0
G. Sediment deposition of dredge materials at Loveladies to fill canals	129,000	90	30	9	4	High	15	11	11	1	1
H. Living shoreline along southern edge of Loveladies	262,500	90	19	9	2	Medium	1	30	11	0	0
ATT											
A. No action	0	99.92	37.75	8	4	High	15	30	11	1	0
B. Remove poles	330,000	99.92	37.75	8	5	High	15	11	11	1	0
C. Dig runnels in most waterlogged areas of site to allow tide water to escape	1,000	99.92	45	8	6	High	30	20	11	1	0
D. Trap mesopredators to increase sparrow population	82,400	99.92	37.75	8	8	High	15	30	11	1	0
E. Create breaks in the roads and berms to increase sheet flow	40,000	99.92	45	8	6	High	30	20	11	1	0
F. Sediment deposition to increase marsh elevation	355,000	90	50	8	7	High	30	11	11	1	1
G. Living shoreline along islands including sediment enrichment	16,500,000	90	50	8	6	High	30	30	11	1	1

Table 3. Possible management actions for achieving objectives within marsh management units at the Edwin B. Forsythe National Wildlife Refuge in New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[%, percent; ppt, parts per thousand]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton density (number of animals per square meter)	Nekton species richness (number)	Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Duration of surface flooding[2]	Surface-water salinity[2] (ppt)	Marsh surface elevation change relative to sea-level rise[3]	Herbicide application (pints per year)
West Creek											
A. No action	0	99.5	27.74	7	3.73	Medium	30	30	11	1	0
B. Living shoreline along east and south edges of marsh	5,625,000	99.5	27.74	7	4	Medium	30	30	11	1	0
C. Sediment enrichment as previously identified to increase elevation of select interior marshes	203,000	90	50	7	7	High	30	11	11	1	1
D. Remove standing dead trees and spray *Phragmites* along woodland edge to facilitate marsh migration	1,000	100	35	7	4.5	Medium	30	30	11	1	4
E. Dig runnels in most waterlogged areas of site to allow tidal water to escape	1,000	99.5	40	7	6	High	30	20	11	1	0
Oceangate											
A. No action	0	93	40.49	5	0.09	Low	15	30	11	0	0
B. Pole removal	220,000	93	40.49	5	3	Medium	15	30	11	0	0
C. Sediment enrichment	129,600	85	55	6	3.5	Medium	30	11	11	1	1
D. Replace culvert under Bayview Avenue to improve tidal flow	365,000	93	65	7	3	Medium	30	30	11	0	0
E. C and D	494,600	92	70	7	3.5	Medium	30	11	11	1	0.5
F. Dig runnels	1,000	93	70	7	3.5	Medium	30	20	11	1	0
Metedeconk River											
A. No action	0	99.2	45.87	7	1.21	Low	15	30	11	1	0
B. Sediment enrichment	137,000	90	55	8	2.5	Medium	30	11	11	1	1
C. Living shoreline along edge by big pond on east side	187,500	99.2	46	7	1.3	Low	30	30	11	1	0
Reedy Creek											
A. No action	0	99.42	13.52	6	1.69	Low	1	30	11	1	0
B. Sediment enrichment	156,200	90	45	8	2.5	Medium	30	11	11	1	1

Table 3. Possible management actions for achieving objectives within marsh management units at the Edwin B. Forsythe National Wildlife Refuge in New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[%, percent; ppt, parts per thousand]

Management action	Estimated cost over 5 years (dollars)	Performance metrics: Native vegetation (% cover)	Nekton density (number of animals per square meter)	Nekton species richness (number)	Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Duration of surface flooding[2]	Surface-water salinity[2] (ppt)	Marsh surface elevation change relative to sea-level rise[3]	Herbicide application (pints per year)
Reedy Creek—Continued											
C. Bridge or crossing to protect Reedy Creek headwaters across sewer right-of-way	200,000	99.42	40	8	2	Low	15	30	11	1	0
D. Living shoreline along various areas of southeast facing shoreline	2,250,000	99.42	14	6	1.7	Low	15	30	11	1	0
Kettle Creek											
A. No action	0	99.88	20.25	8	2.59	Low	1	30	11	0	0
B. Sediment enrichment on east side, avoiding multiple-ownership lands	129,900	90	40	8	3	Low	30	11	11	1	1
North Barnegat Bay Islands											
A. No action	0	95.2	52.42	8	3.59	Low	1	30	11	1	0
B. Sediment enrichment on north end of large islands	126,600	90	60	9	4	Low	30	11	11	1	1
C. *Phragmites* control	340	100	60	9	4	Low	15	30	11	1	4
D. Add runnel between crescents to improve tidal flow to westernmost crescent pond on south end	1,000	98	65	9	4	Low	15	11	11	1	0
Good Luck Point											
A. No action	0	97.88	31.54	7	1.11	Low	15	30	11	1	0
B. Pole removal	825,600	97.88	31.54	7	3	Medium	15	30	11	1	0
C. Create breaks in the roads and berms to increase sheet flow	1,000	98	45	8	2	Low	30	20	11	1	0
D. Living shoreline along various areas of southeast facing shoreline	225,000	98	32	7	1.5	Low	30	30	11	1	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Edwin B. Forsythe National Wildlife Refuge in New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[%, percent; ppt, parts per thousand]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton density (number of animals per square meter)	Nekton species richness (number)	Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Duration of surface flooding[2]	Surface-water salinity[2] (ppt)	Marsh surface elevation change relative to sea-level rise[3]	Herbicide application (pints per year)
Stouts Creek											
A. No action	0	93	54.86	7	1.23	Medium	15	30	11	1	0
B. Breach berms at impoundment to improve tidal flow	0	95	65	8	3	Medium	30	11	11	1	0
C. Sediment enrichment, especially after berm breaching	161,000	88	70	8	2.5	Medium	30	11	11	1	1
D. Remove standing dead trees and spray *Phragmites* along woodland edge to facilitate marsh migration	2,000	100	65	7	3	Medium	15	30	11	1	4
E. Living shoreline along various areas of southeast facing shoreline	1,875,000	93	55	7	1.5	Medium	30	30	11	1	0
Barnegat											
A. No action	0	95.86	31.71	8	3.88	High	1	30	11	1	0
B. Breach berms at impoundment to improve tidal flow	0	97	50	9	5	High	1	11	11	1	0
C. Sediment enrichment and berm breaching	235,000	89	55	9	4.5	High	15	11	11	1	1
D. Remove standing dead trees and spray *Phragmites* along woodland edge to facilitate marsh migration	3,000	100	40	8	4.5	High	1	30	11	1	4
E. Living shoreline along Double Creek	3,000,000	95.86	31.71	8	4	High	1	30	11	1	0
F. *Phragmites* control	2,550	100	40	8	4.5	High	1	30	11	1	4
G. Replace undersized culvert on Bayshore Drive	208,216	97	57	9	5	High	1	11	11	1	0
Cedar Bonnet Island											
A. No action	0	98.4	30.78	10	6.97	Low	15	30	11	1	4
B. Living shoreline along various areas of southeast facing shoreline	300,000	98.4	30.78	10	7	Low	15	30	11	1	4
C. Improve tidal flushing south of Route 72	250,000	99	65	10	8	Medium	30	11	11	1	2

Table 3. Possible management actions for achieving objectives within marsh management units at the Edwin B. Forsythe National Wildlife Refuge in New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[%, percent; ppt, parts per thousand]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegeta-tion (% cover)	Nekton density (number of animals per square meter)	Nekton species richness (num-ber)	Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Duration of surface flood-ing[2]	Surface-water salinity[2] (ppt)	Marsh surface elevation change rela-tive to sea-level rise[3]	Herbicide applica-tion (pints per year)
Little Egg South											
A. No action	0	99.5	94.82	8	7.37	Medium	15	30	11	0	0
B. Dig runnels in most waterlogged areas of site to allow tidal water to escape	1,000	99.5	110	10	8	Medium	15	20	11	1	0
C. Sediment enrichment	215,000	90	100	9	8	Medium	30	11	11	1	1
D. Living shoreline along various areas of southeast facing shoreline	1,875,000	99.5	94.82	8	7.5	Medium	15	30	11	1	0
Oyster Creek											
A. No action	0	96.92	49.04	7	7	High	15	30	11	1	0
B. Remove standing dead trees and spray *Phragmites* along woodland edge to facilitate marsh migration	2,000	100	55	8	7.5	High	15	30	11	1	4
C. Living shoreline along eastern edge	1,687,500	96.92	49.04	7	7	High	15	30	11	1	0
Little Egg Islands											
A. No action	0	74.83	41.18	6	5.08	Medium	15	30	11	1	0
B. Living shoreline as needed	1,406,250	74.83	41.18	6	5.5	Medium	15	30	11	1	0
C. Sediment enrichment	134,000	70	65	8	6.5	Medium	30	11	11	1	1
Motts-Mullica Wilderness											
A. No action	0	99.92	50.71	8	5.21	High	15	30	11	1	0
B. Plug and place sediment in the Long Ditch in northwest section	225,000	95	55	9	6	High	15	11	11	1	1
Bass River-Ballanger											
A. No action	0	93.67	40.11	9	5.89	High	15	30	11	1	0
B. Remove standing dead trees and spray *Phragmites* along woodland edge to facilitate marsh migration	2,000	100	50	10	7	High	15	30	11	1	4
C. Living shoreline at Graveling Point	1,612,500	93.67	40.11	9	6	High	15	30	11	1	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Edwin B. Forsythe National Wildlife Refuge in New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[%, percent; ppt, parts per thousand]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegeta-tion (% cover)	Nekton density (number of animals per square meter)	Nekton species richness (num-ber)	Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Duration of surface flood-ing[2]	Surface-water salinity[2] (ppt)	Marsh surface elevation change rela-tive to sea-level rise[3]	Herbicide applica-tion (pints per year)
Forked River											
A. No action	0	96.25	22.49	9	1.46	Low	1	30	11	1	0
B. Breach berms at Wrangle Road	0	97	55	10	2	Low	1	11	11	1	0
C. Breach road on west edge to allow tidal flow	1,000	97	55	10	2	Low	1	11	11	1	0
Little Beach-Holgate											
A. No action	0	99.42	25.94	10	1.29	High	1	11	11	0	0
B. Create marsh habitat on west edge of Holgate	2,500	100	65	10	6	High	15	11	11	1	0
C. Spray *Phragmites* in marsh transition zone to reduce encroachment onto beach at Holgate	85	100	45	10	3	High	1	11	11	0	4
Cedar Run											
A. No action	0	97	47	7	7.59	High	1	11	11	1	0
B. Breach berms along Mill Creek to increase tidal flow	20,000	98	65	9	8	High	1	11	11	1	0
C. Build ditch plug, sediment enrichment and planting of unnatural features from previous construction	138,700	92	65	8	8	High	15	11	11	1	1
D. Restore open water salt hay farms to marsh	248,700	100	70	9	9	High	30	11	11	1	0
E. Remove standing dead trees and spray *Phragmites* along woodland edge to facilitate marsh migration	2,000	100	50	8	8	High	1	11	11	1	4
F. Living shoreline along south edge Popular Point	3,375,000	97	47	7	7.75	High	1	11	11	1	0
Nacote Creek-Motts Creek											
A. No action	0	99.5	14.22	5	4.74	High	15	30	11	0	0
B. Remove standing dead trees and spray *Phragmites* along woodland edge to facilitate marsh migration	2,000	100	20	6	5.5	High	15	30	11	0	4
C. Living shoreline along Mullica River	1,125,000	99.5	14.22	5	5	High	15	30	11	1	0
D. Living shoreline along human-made cut-throughs	375,000	99.5	14.22	5	5	High	15	30	11	1	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Edwin B. Forsythe National Wildlife Refuge in New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[%, percent; ppt, parts per thousand]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegeta-tion (% cover)	Nekton density (number of animals per square meter)	Nekton species richness (num-ber)	Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Duration of surface flood-ing[2]	Surface-water salinity[2] (ppt)	Marsh surface elevation change rela-tive to sea-level rise[3]	Herbicide applica-tion (pints per year)
Nacote Creek West											
A. No action	0	83.25	5.99	7	1.15	Low	15	11	11	1	0
B. Living shoreline along Nacote Creek	862,500	83.25	5.99	7	1.3	Low	15	11	11	1	0
Reeds Bay-Hammock Cove											
A. No action	0	98.58	31.25	8	4.1	High	1	30	11	0	0
B. Living shoreline along various areas of southeast facing shoreline	3,750,000	98.58	31.25	8	4.3	High	1	30	11	1	0

[1]Relative abundance for refuge during wintering waterfowl season.

[2]Measures absolute deviation from reference point representing ideal condition.

[3]Measures change relative to sea-level rise: 0, lower than sea-level rise; 1, above sea-level rise.

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within marsh management units at the at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics.]

Management action	Performance metrics										Total management benefit
	Native vegetation	Nekton density	Nekton species richness	Tidal marsh obligate birds	American black ducks	Spider density	Duration of surface flooding	Surface-water salinity	Marsh surface elevation change	Herbicide application	
Loveladies Vol Sedge Clam											
A. No action	0.120	0.014	0.041	0.022	0.075	0	0.037	0.103	0	0.06	0.471
B. Sediment deposition of dredge materials on Clam Island to increase elevation and enlarge marsh area	0.116	0.021	0.041	0.044	0.1	0.045	0.106	0.103	0.22	0.045	0.840
C. Living shoreline along southwest edge of Clam Island	0.116	0.014	0.041	0.022	0.075	0	0.037	0.103	0	0.06	0.467
D. Sediment deposition of dredge materials on High Bar Island to increase elevation and enlarge marsh area	0.116	0.021	0.041	0.044	0.1	0.045	0.106	0.103	0.22	0.045	0.840
E. Living shoreline along southwest edge of High Bar Island	0.116	0.014	0.041	0.022	0.075	0	0.037	0.103	0	0.06	0.467
F. Living shoreline at Vol Sedge	0.116	0.014	0.041	0.022	0.075	0	0.037	0.103	0.22	0.06	0.687
G. Sediment deposition of dredge materials at Loveladies to fill canals	0.116	0.021	0.041	0.044	0.1	0.045	0.106	0.103	0.22	0.045	0.840
H. Living shoreline along southern edge of Loveladies	0.116	0.014	0.041	0.022	0.075	0	0.037	0.103	0	0.06	0.467
ATT											
A. No action	0.120	0.025	0.036	0.044	0.1	0.045	0.037	0.103	0.22	0.06	0.789
B. Remove poles	0.120	0.025	0.036	0.056	0.1	0.045	0.106	0.103	0.22	0.06	0.870
C. Dig runnels in most waterlogged areas of site to allow tide water to escape	0.120	0.028	0.036	0.067	0.1	0.09	0.073	0.103	0.22	0.06	0.896
D. Trap meso-predators to increase sparrow population	0.120	0.025	0.036	0.089	0.1	0.045	0.037	0.103	0.22	0.06	0.834
E. Create breaks in the roads andberms to increase sheet flow	0.120	0.028	0.036	0.067	0.1	0.09	0.073	0.103	0.22	0.06	0.896
F. Sediment deposition to increase marsh elevation	0.116	0.030	0.036	0.078	0.1	0.09	0.106	0.103	0.22	0.045	0.923

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within marsh management units at the at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics.]

Management action	Performance metrics										Total management benefit
	Native vegetation	Nekton density	Nekton species richness	Tidal marsh obligate birds	American black ducks	Spider density	Duration of surface flooding	Surface-water salinity	Marsh surface elevation change	Herbicide application	
ATT—Continued											
G. Living shoreline along islands including sediment enrichment	0.116	0.030	0.036	0.067	0.1	0.09	0.037	0.103	0.22	0.045	0.843
West Creek											
A. No action	0.120	0.019	0.032	0.041	0.075	0.09	0.037	0.103	0.22	0.06	0.797
B. Living shoreline along east and south edges of marsh	0.120	0.019	0.032	0.044	0.075	0.09	0.037	0.103	0.22	0.06	0.800
C. Sediment enrichment as previously identified to increase elevation of select interior marshes	0.116	0.030	0.032	0.078	0.1	0.09	0.106	0.103	0.22	0.045	0.919
D. Remove standing dead trees and spray Phragmites along woodland edge to facilitate marsh migration	0.120	0.023	0.032	0.050	0.075	0.09	0.037	0.103	0.22	0	0.749
E. Dig runnels in most waterlogged areas of site to allow tidal water to escape	0.120	0.026	0.032	0.067	0.1	0.09	0.073	0.103	0.22	0.06	0.890
Oceangate											
A. No action	0.117	0.026	0.023	0.001	0	0.045	0.037	0.103	0	0.06	0.411
B. Pole removal	0.117	0.026	0.023	0.033	0.075	0.045	0.037	0.103	0	0.06	0.518
C. Sediment enrichment	0.113	0.032	0.027	0.039	0.075	0.09	0.106	0.103	0.22	0.045	0.850
D. Replace culvert under Bayview Avenue to improve tidal flow	0.117	0.035	0.032	0.033	0.075	0.09	0.037	0.103	0	0.06	0.581
E. C and D	0.117	0.037	0.032	0.039	0.075	0.09	0.106	0.103	0.22	0.0525	0.870
F. Dig runnels	0.117	0.037	0.032	0.039	0.075	0.09	0.073	0.103	0.22	0.06	0.845
Metedeconk River											
A. No action	0.120	0.028	0.032	0.013	0	0.045	0.037	0.103	0.22	0.06	0.657
B. Sediment enrichment	0.116	0.032	0.036	0.028	0.075	0.09	0.106	0.103	0.22	0.045	0.850
C. Living shoreline along edge by big pond on east side	0.120	0.028	0.032	0.014	0	0.09	0.037	0.103	0.22	0.06	0.703

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within marsh management units at the at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics.]

Management action	Performance metrics										Total management benefit
	Native vegetation	Nekton density	Nekton species richness	Tidal marsh obligate birds	American black ducks	Spider density	Duration of surface flooding	Surface-water salinity	Marsh surface elevation change	Herbicide application	
Reedy Creek											
A. No action	0.120	0.011	0.027	0.019	0	0	0.037	0.103	0.22	0.06	0.595
B. Sediment enrichment	0.116	0.028	0.036	0.028	0.075	0.09	0.106	0.103	0.22	0.045	0.846
C. Bridge or crossing to protect Reedy Creek headwaters across sewer right-of-way	0.120	0.026	0.036	0.022	0	0.045	0.037	0.103	0.22	0.06	0.668
D. Living shoreline along various areas of southeast facing shoreline	0.120	0.011	0.027	0.019	0	0.045	0.037	0.103	0.22	0.06	0.641
Kettle Creek											
A. No action	0.120	0.015	0.036	0.029	0	0	0.037	0.103	0	0.06	0.399
B. Sediment enrichment on east side, avoiding multiple-ownership lands	0.116	0.026	0.036	0.033	0	0.09	0.106	0.103	0.22	0.045	0.775
North Barnegat Bay Islands											
A. No action	0.118	0.031	0.036	0.040	0	0	0.037	0.103	0.22	0.06	0.644
B. Sediment enrichment on north end of large islands	0.116	0.033	0.041	0.044	0	0.09	0.106	0.103	0.22	0.045	0.798
C. Phragmites control	0.120	0.033	0.041	0.044	0	0.045	0.037	0.103	0.22	0	0.643
D. Add runnel between crescents to improve tidal flow to westernmost crescent pond on south end	0.119	0.035	0.041	0.044	0	0.045	0.106	0.103	0.22	0.06	0.773
Good Luck Point											
A. No action	0.119	0.021	0.032	0.012	0	0.045	0.037	0.103	0.22	0.06	0.649
B. Pole removal	0.119	0.021	0.032	0.033	0.075	0.045	0.037	0.103	0.22	0.06	0.745
C. Create breaks in the roads andberms to increase sheet flow	0.119	0.028	0.036	0.022	0	0.09	0.073	0.103	0.22	0.06	0.751
D. Living shoreline along various areas of southeast facing shoreline	0.119	0.022	0.032	0.017	0	0.09	0.037	0.103	0.22	0.06	0.698

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within marsh management units at the at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics.]

Management action	Performance metrics										Total management benefit
	Native vegetation	Nekton density	Nekton species richness	Tidal marsh obligate birds	American black ducks	Spider density	Duration of surface flooding	Surface-water salinity	Marsh surface elevation change	Herbicide application	
Stouts Creek											
A. No action	0.117	0.032	0.032	0.014	0.075	0.045	0.037	0.103	0.22	0.06	0.733
B. Breach berms at impoundment to improve tidal flow	0.118	0.035	0.036	0.033	0.075	0.09	0.106	0.103	0.22	0.06	0.876
C. Sediment enrichment, especially after berm breaching	0.115	0.037	0.036	0.028	0.075	0.09	0.106	0.103	0.22	0.045	0.854
D. Remove standing dead trees and spray Phragmites along woodland edge to facilitate marsh migration	0.120	0.035	0.032	0.033	0.075	0.045	0.037	0.103	0.22	0	0.699
E. Living shoreline along various areas of southeast facing shoreline	0.117	0.032	0.032	0.017	0.075	0.09	0.037	0.103	0.22	0.06	0.781
Barnegat											
A. No action	0.118	0.022	0.036	0.043	0.1	0	0.037	0.103	0.22	0.06	0.738
B. Breach berms at impoundment to improve tidal flow	0.119	0.030	0.041	0.056	0.1	0	0.106	0.103	0.22	0.06	0.834
C. Sediment enrichment and berm breaching	0.115	0.032	0.041	0.050	0.1	0.045	0.106	0.103	0.22	0.045	0.857
D. Remove standing dead trees and spray Phragmites along woodland edge to facilitate marsh migration	0.120	0.026	0.036	0.050	0.1	0	0.037	0.103	0.22	0	0.691
E. Living shoreline along Double Creek	0.118	0.022	0.036	0.044	0.1	0	0.037	0.103	0.22	0.06	0.740
F. Phragmites control	0.120	0.026	0.036	0.050	0.1	0	0.037	0.103	0.22	0	0.691
G. Replace undersized culvert on Bayshore Drive	0.119	0.032	0.041	0.056	0.1	0	0.106	0.103	0.22	0.06	0.836
Cedar Bonnet Island											
A. No action	0.119	0.021	0.045	0.077	0	0.045	0.037	0.103	0.22	0	0.667
B. Living shoreline along various areas of southeast facing shoreline	0.119	0.021	0.045	0.078	0	0.045	0.037	0.103	0.22	0	0.668
C. Improve tidal flushing south of Route 72	0.120	0.035	0.045	0.089	0.075	0.09	0.106	0.103	0.22	0.03	0.913

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within marsh management units at the at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics.]

Management action	Performance metrics										Total management benefit
	Native vegetation	Nekton density	Nekton species richness	Tidal marsh obligate birds	American black ducks	Spider density	Duration of surface flooding	Surface-water salinity	Marsh surface elevation change	Herbicide application	
Little Egg South											
A. No action	0.120	0.042	0.036	0.082	0.075	0.045	0.037	0.103	0	0.06	0.599
B. Dig runnels in most waterlogged areas of site to allow tidal water to escape	0.120	0.045	0.045	0.089	0.075	0.045	0.073	0.103	0.22	0.06	0.875
C. Sediment enrichment	0.116	0.043	0.041	0.089	0.075	0.09	0.106	0.103	0.22	0.045	0.928
D. Living shoreline along various areas of southeast facing shoreline	0.120	0.042	0.036	0.083	0.075	0.045	0.037	0.103	0.22	0.06	0.821
Oyster Creek											
A. No action	0.119	0.029	0.032	0.078	0.1	0.045	0.037	0.103	0.22	0.06	0.822
B. Remove standing dead trees and spray Phragmites along woodland edge to facilitate marsh migration	0.120	0.032	0.036	0.083	0.1	0.045	0.037	0.103	0.22	0	0.775
C. Living shoreline along eastern edge	0.119	0.029	0.032	0.078	0.1	0.045	0.037	0.103	0.22	0.06	0.822
Little Egg Islands											
A. No action	0.108	0.026	0.027	0.056	0.075	0.045	0.037	0.103	0.22	0.06	0.757
B. Living shoreline as needed	0.108	0.026	0.027	0.061	0.075	0.045	0.037	0.103	0.22	0.06	0.761
C. Sediment enrichment	0.105	0.035	0.036	0.072	0.075	0.09	0.106	0.103	0.22	0.045	0.887
Motts-Mullica Wilderness											
A. No action	0.120	0.030	0.036	0.058	0.1	0.045	0.037	0.103	0.22	0.06	0.808
B. Plug and place sediment in the Long Ditch in northwest section	0.118	0.032	0.041	0.067	0.1	0.045	0.106	0.103	0.22	0.045	0.876
Bass River-Ballanger											
A. No action	0.117	0.026	0.041	0.065	0.1	0.045	0.037	0.103	0.22	0.06	0.813
B. Remove standing dead trees and spray Phragmites along woodland edge to facilitate marsh migration	0.120	0.030	0.045	0.078	0.1	0.045	0.037	0.103	0.22	0	0.777
C. Living shoreline at Graveling Point	0.117	0.026	0.041	0.067	0.1	0.045	0.037	0.103	0.22	0.06	0.815

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within marsh management units at the at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics.]

Management action	Performance metrics										Total management benefit
	Native vegetation	Nekton density	Nekton species richness	Tidal marsh obligate birds	American black ducks	Spider density	Duration of surface flooding	Surface-water salinity	Marsh surface elevation change	Herbicide application	
Forked River											
A. No action	0.119	0.016	0.041	0.016	0	0	0.037	0.103	0.22	0.06	0.611
B. Breach berms at Wrangle Road	0.119	0.032	0.045	0.022	0	0	0.106	0.103	0.22	0.06	0.707
C. Breach berm road on west edge to allow tidal flow	0.119	0.032	0.045	0.022	0	0	0.106	0.103	0.22	0.06	0.707
Little Beach-Holgate											
A. No action	0.120	0.018	0.045	0.014	0.1	0	0.106	0.103	0	0.06	0.567
B. Create marsh habitat on west edge of Holgate	0.120	0.035	0.045	0.067	0.1	0.045	0.106	0.103	0.22	0.06	0.901
C. Spray Phragmites in marsh transition zone to reduce encroachment onto beach at Holgate	0.120	0.028	0.045	0.033	0.1	0	0.106	0.103	0	0	0.535
Cedar Run											
A. No action	0.119	0.029	0.032	0.084	0.1	0	0.106	0.103	0.22	0.06	0.852
B. Breach berms along Mill Creek to increase tidal flow	0.119	0.035	0.041	0.089	0.1	0	0.106	0.103	0.22	0.06	0.873
C. Build ditch plug, sediment enrichment and planting of unnatural features from previous construction	0.117	0.035	0.036	0.089	0.1	0.045	0.106	0.103	0.22	0.045	0.896
D. Restore open water salt hay farms to marsh	0.120	0.037	0.041	0.100	0.1	0.09	0.106	0.103	0.22	0.06	0.976
E. Remove standing dead trees and spray Phragmites along woodland edge to facilitate marsh migration	0.120	0.030	0.036	0.089	0.1	0	0.106	0.103	0.22	0	0.804
F. Living shoreline along south edge Popular Point	0.119	0.029	0.032	0.086	0.1	0	0.106	0.103	0.22	0.06	0.854

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within marsh management units at the at the Edwin B. Forsythe National Wildlife Refuge in New Jersey.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics.]

Management action	Performance metrics										Total management benefit
	Native vegetation	Nekton density	Nekton species richness	Tidal marsh obligate birds	American black ducks	Spider density	Duration of surface flooding	Surface-water salinity	Marsh surface elevation change	Herbicide application	
Nacote Creek-Motts Creek											
A. No action	0.120	0.011	0.023	0.053	0.1	0.045	0.037	0.103	0	0.06	0.550
B. Remove standing dead trees and spray Phragmites along woodland edge to facilitate marsh migration	0.120	0.015	0.027	0.061	0.1	0.045	0.037	0.103	0	0	0.507
C. Living shoreline along Mullica River	0.120	0.011	0.023	0.056	0.1	0.045	0.037	0.103	0.22	0.06	0.773
D. Living shoreline along human-made cut-throughs	0.120	0.011	0.023	0.056	0.1	0.045	0.037	0.103	0.22	0.06	0.773
Nacote Creek West											
A. No action	0.113	0.005	0.032	0.013	0	0.045	0.106	0.103	0.22	0.06	0.696
B. Living shoreline along Nacote Creek	0.113	0.005	0.032	0.014	0	0.045	0.106	0.103	0.22	0.06	0.697
Reeds Bay-Hammock Cove											
A. No action	0.119	0.021	0.036	0.046	0.1	0	0.037	0.103	0	0.06	0.522
B. Living shoreline along various areas of southeast facing shoreline	0.119	0.021	0.036	0.048	0.1	0	0.037	0.103	0.22	0.06	0.744

Appendix 1. Regional Influence Diagrams

The influence diagrams (following the style of prototype diagrams in Neckles and others, 2015) in this appendix (figs. 1.1–1.8) relate possible management strategies to performance metrics. Shapes represent elements of decisions, as follows: rectangles for actions, rectangles with rounded corners for deterministic factors, ovals for stochastic events, and hexagons for consequences expressed as a performance metric.

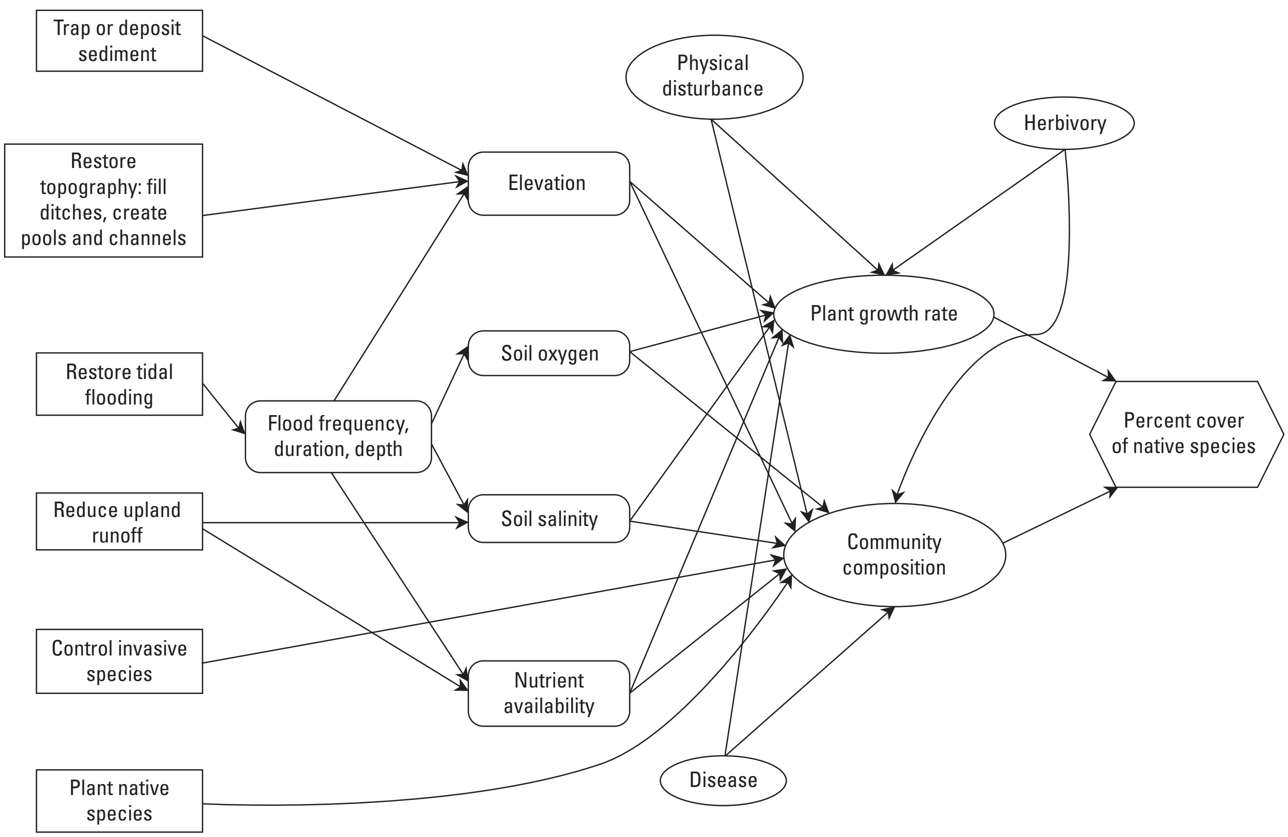


Figure 1.1. Influence diagram used to estimate percent cover of native vegetation in response to implementing certain management actions.

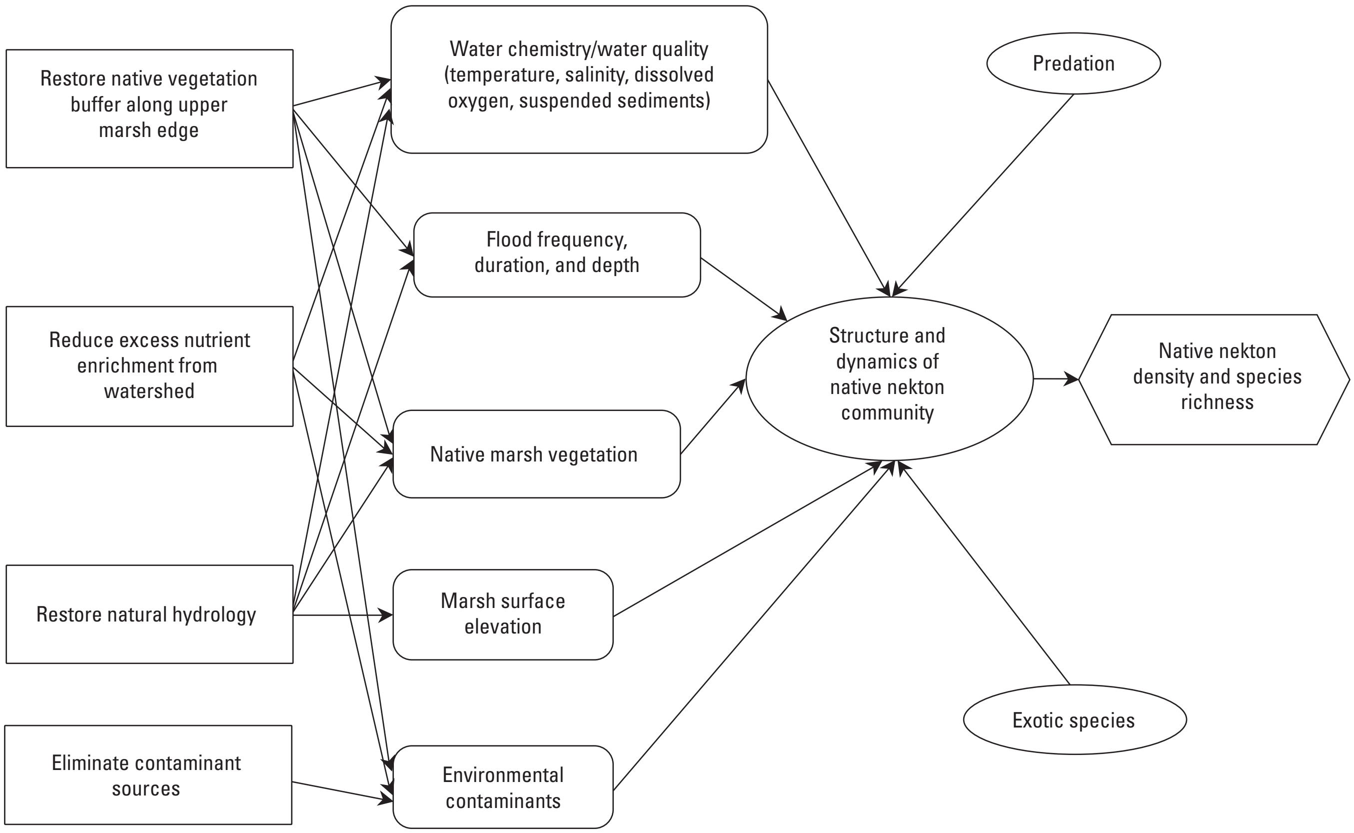


Figure 1.2. Influence diagram used to estimate nekton density and species richness in response to implementing certain management actions.

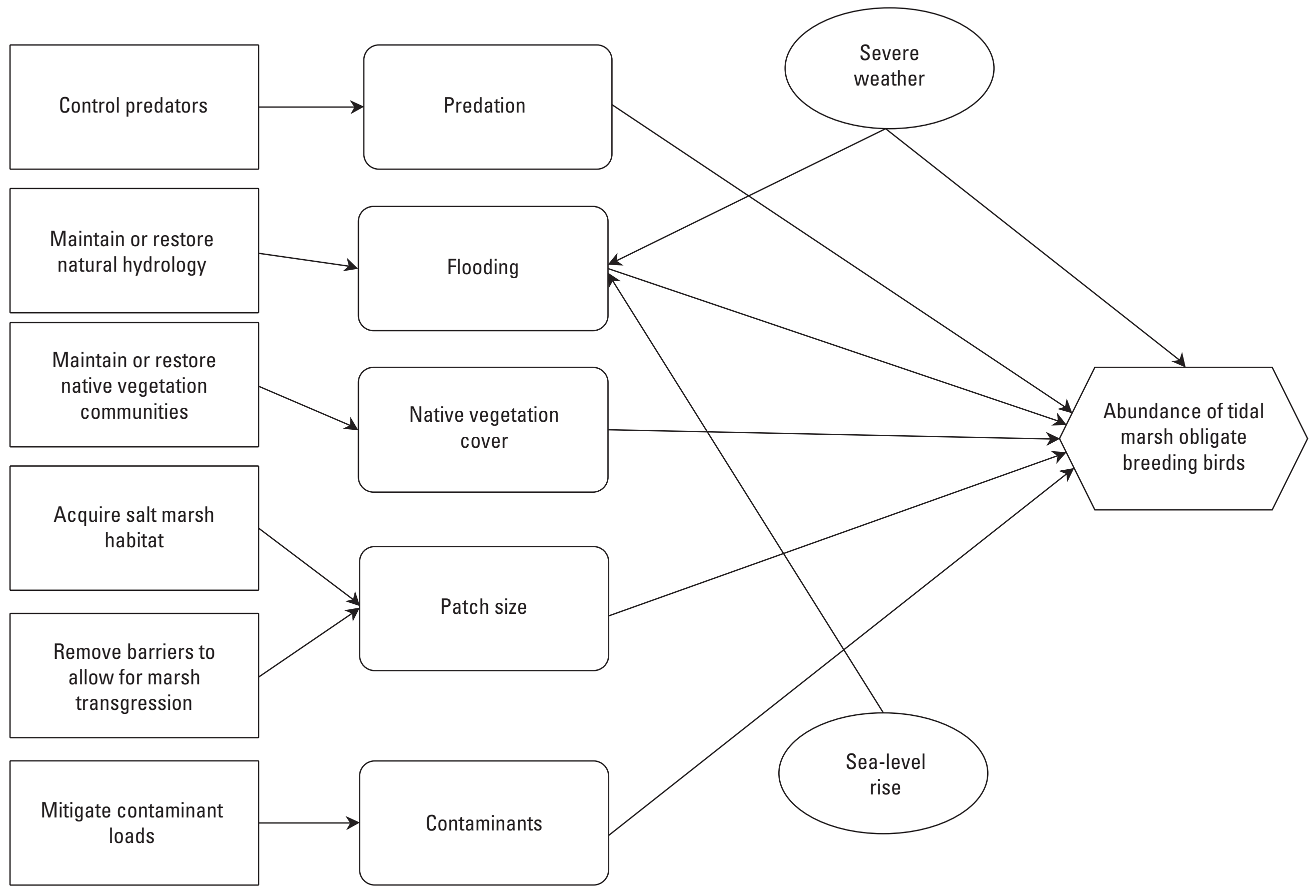


Figure 1.3. Influence diagram used to estimate abundance of tidal marsh obligate breeding birds in response to implementing certain management actions.

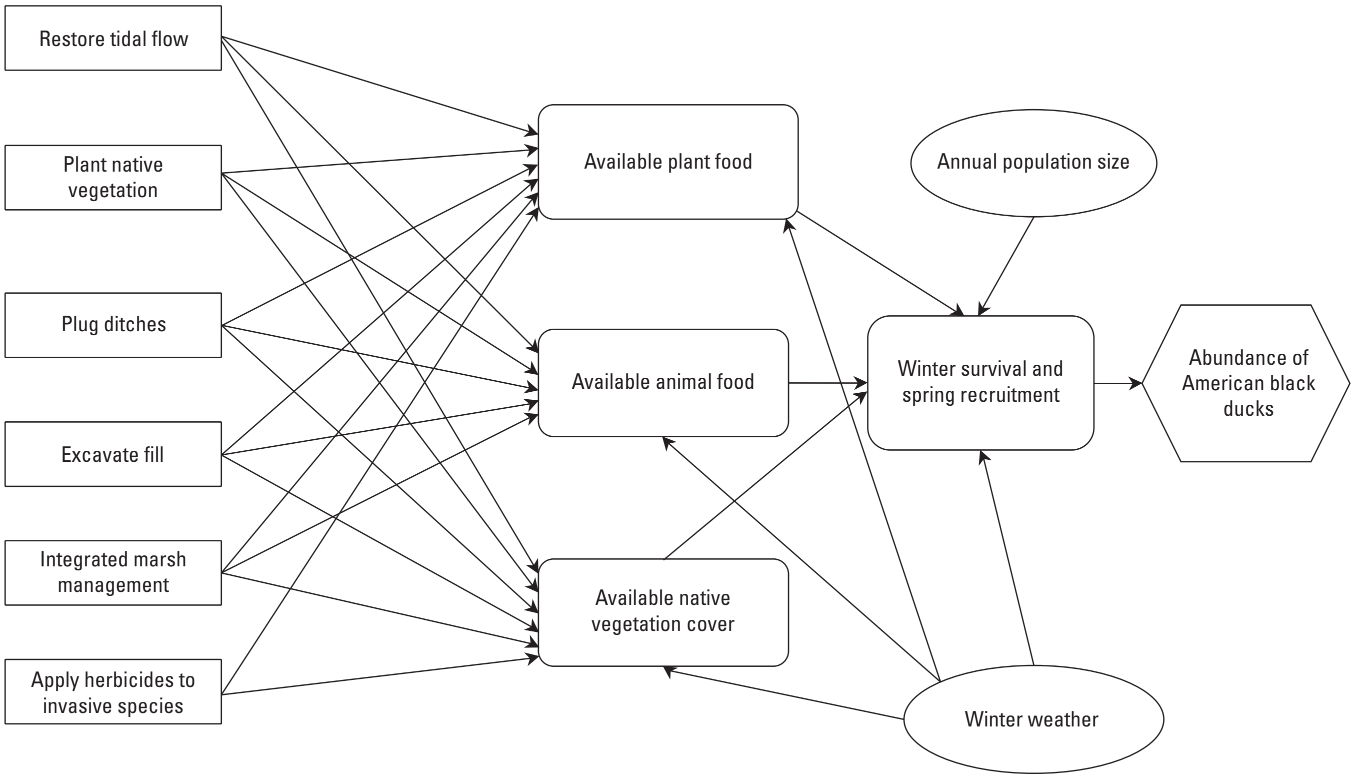


Figure 1.4. Influence diagram used to estimate abundance of American black ducks in winter, as indicator species for nonbreeding wetland birds, in response to implementing certain management actions.

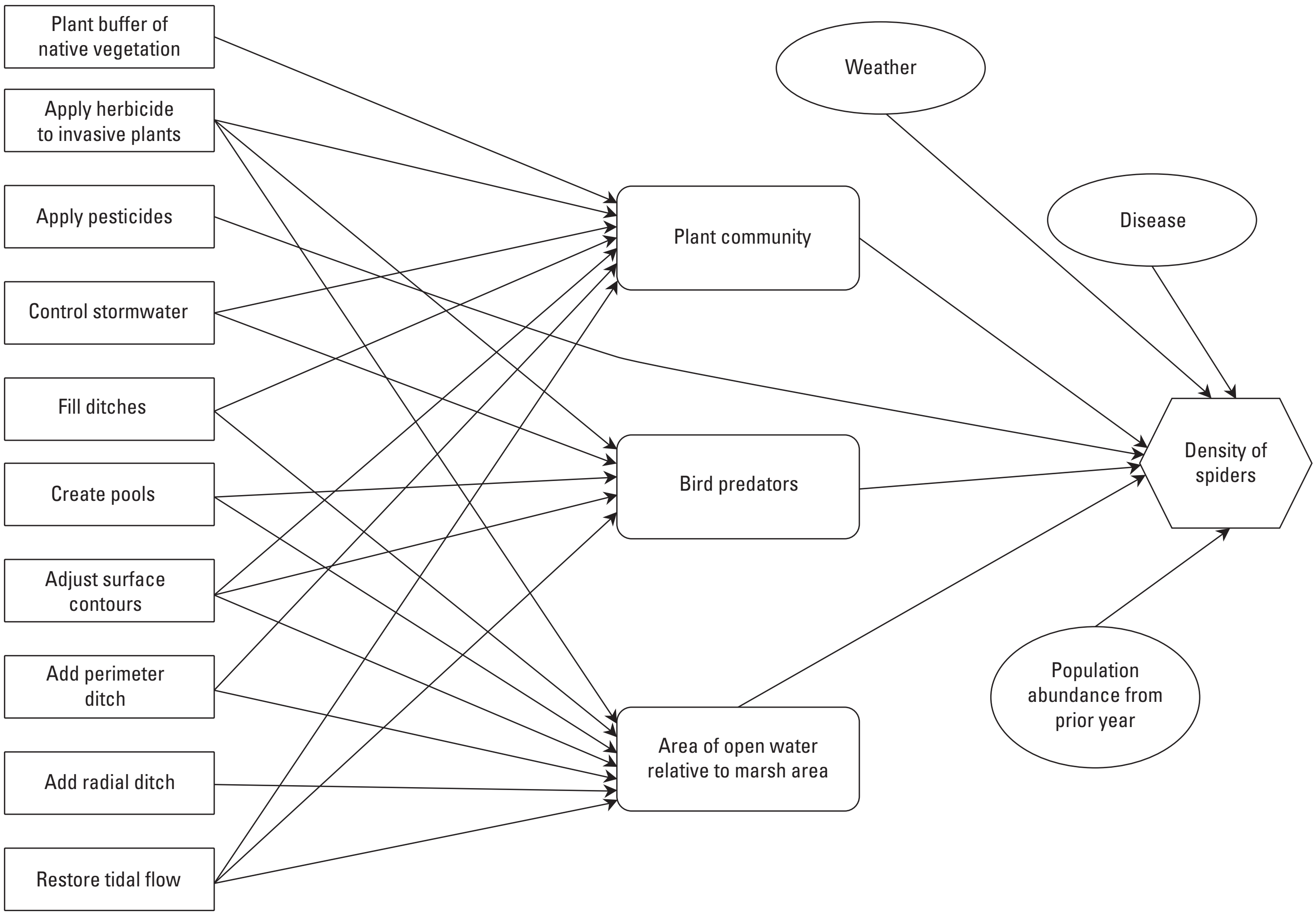


Figure 1.5. Influence diagram used to estimate density of spiders, as indicator of trophic health, in response to implementing certain management actions.

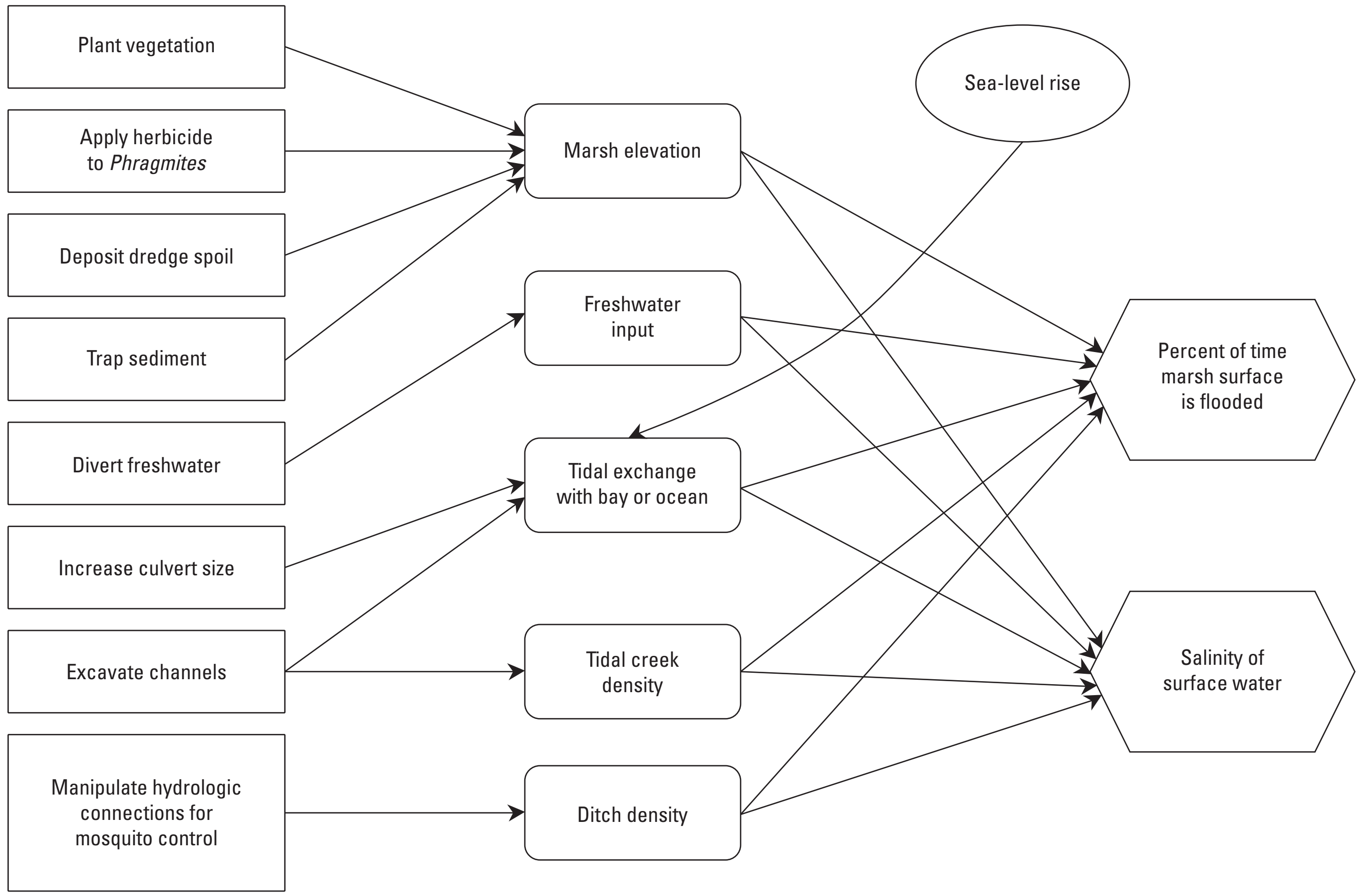


Figure 1.6. Influence diagram used to estimate percent of time marsh surface is flooded and salinity of marsh surface water in response to implementing certain management actions.

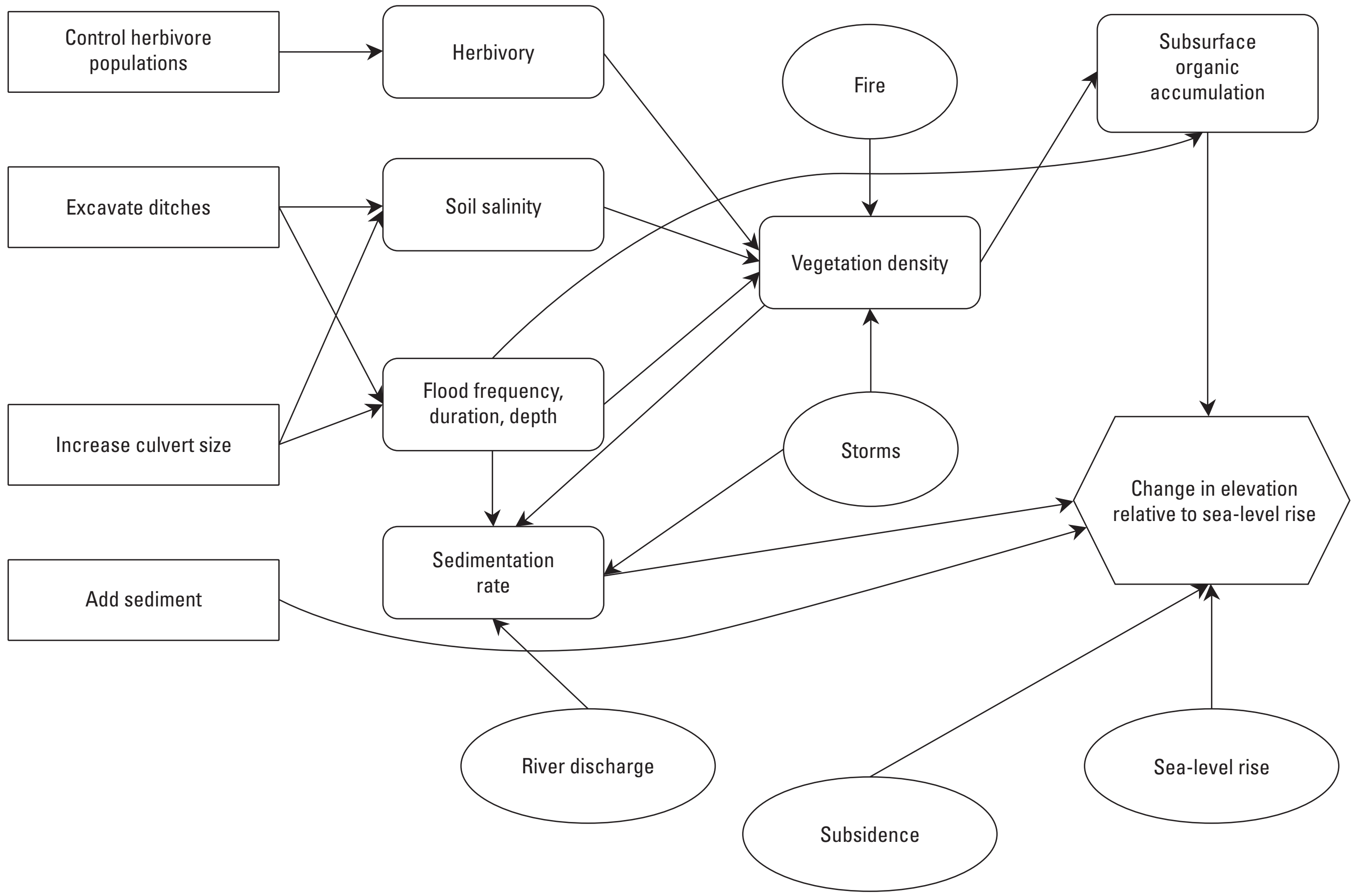


Figure 1.7. Influence diagram used to estimate change in elevation of the marsh surface relative to sea-level rise in response to implementing certain management actions.

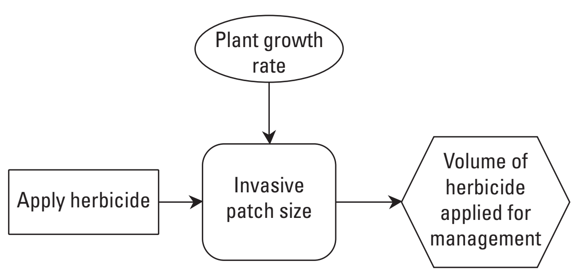


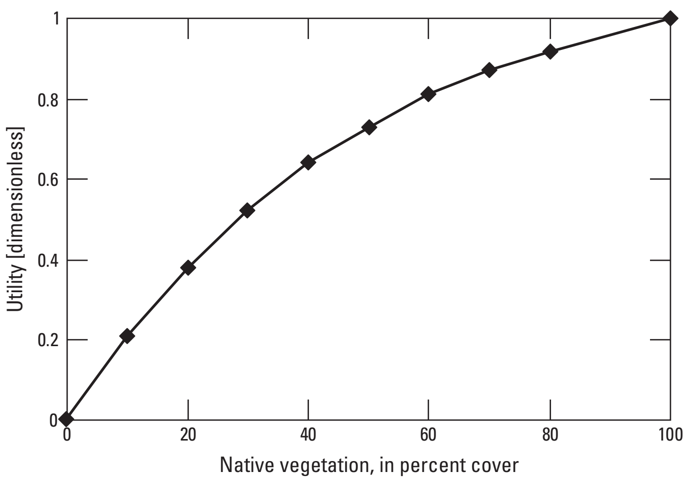
Figure 1.8. Influence diagram used to estimate volume of herbicide that could be applied if a decision was made to use chemical control for removing unwanted vegetation.

Reference Cited

Neckles, H.A., Lyons, J.E., Guntenspergen, G.R., Shriver, W.G., and Adamowicz, S.C., 2015, Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems: Estuaries and Coasts, v. 38, no. 4, p. 1215–1232. [Also available at https://doi.org/10.1007/s12237-014-9822-5.]

Appendix 2. Utility Functions for the Edwin B. Forsythe National Wildlife Refuge

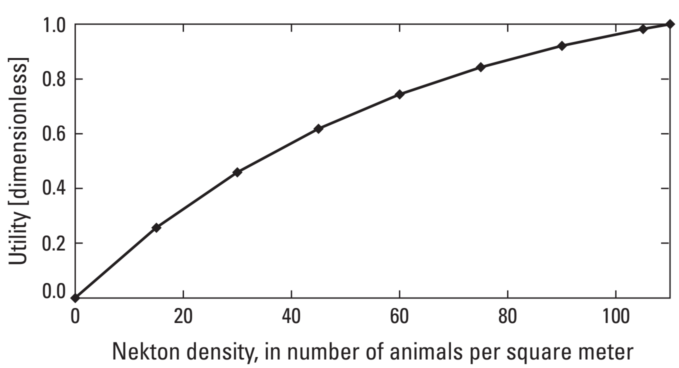
Utilities [$u(x)$] are derived as monotonically increasing, monotonically decreasing, or step functions over the range of performance metric x. In the functions in figures 2.1 to 2.10, x, *Low*, *High*, and ρ are expressed in performance metric units; *Low* and *High* represent the endpoints of the given metric range for the Edwin B. Forsythe National Wildlife Refuge; and ρ represents a shape parameter derived by stakeholder elicitation (Neckles and others, 2015). Break points in step functions were also derived by stakeholder elicitation.



$$u(x) = \frac{1 - e^{\frac{-(x - Low)}{\rho}}}{1 - e^{\frac{-(High - Low)}{\rho}}}$$

where
Low = 0
High = 100
ρ = 50

Figure 2.1. Native vegetation at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.



$$u(x) = \frac{1 - e^{\frac{-(x - Low)}{\rho}}}{1 - e^{\frac{-(High - Low)}{\rho}}}$$

where
Low = 0
High = 110
ρ = 63

Figure 2.2. Native nekton density at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

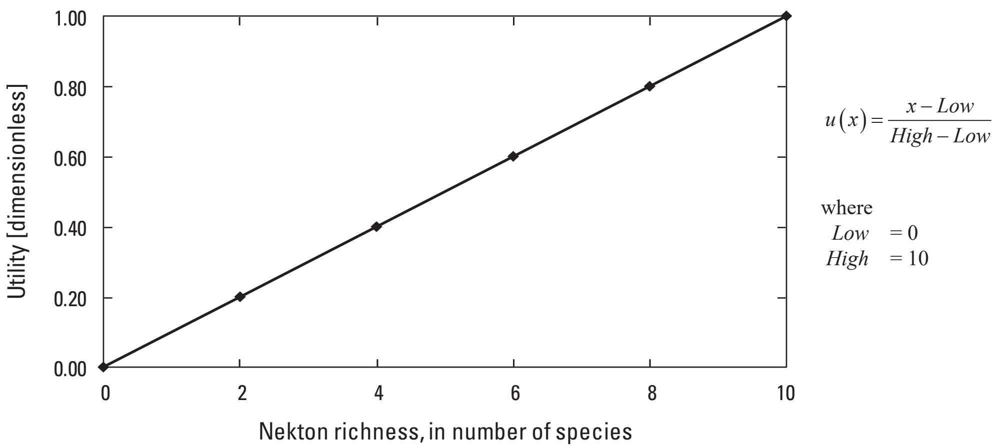


Figure 2.3. Native nekton species richness at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

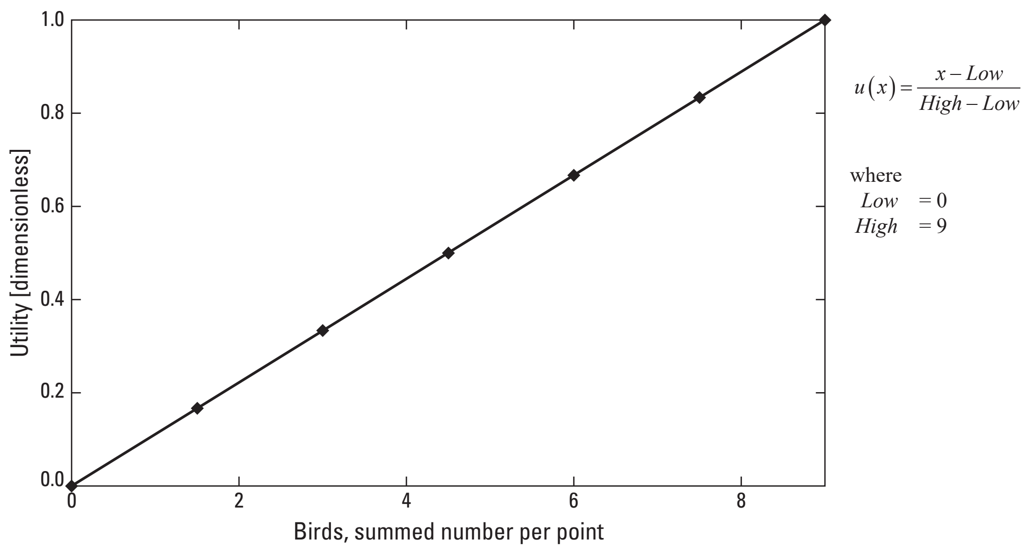


Figure 2.4. Tidal marsh obligate birds at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

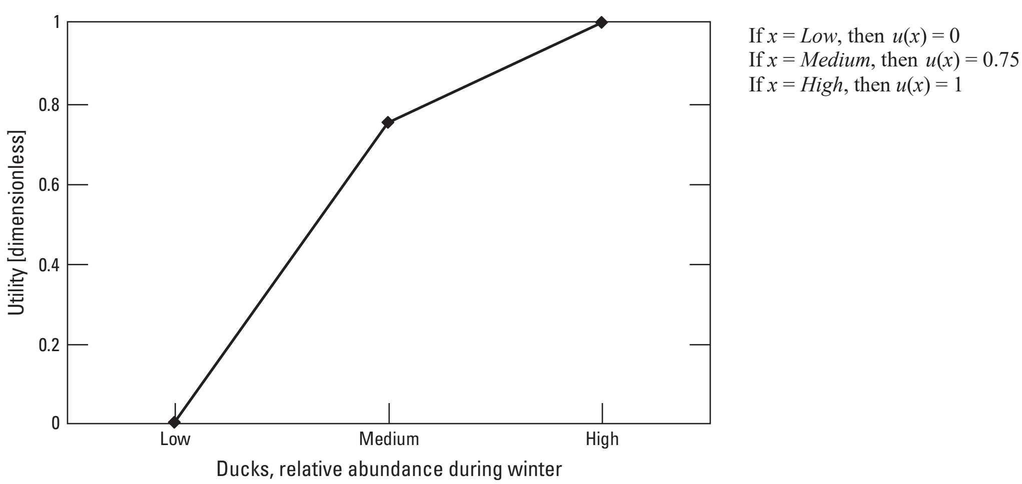
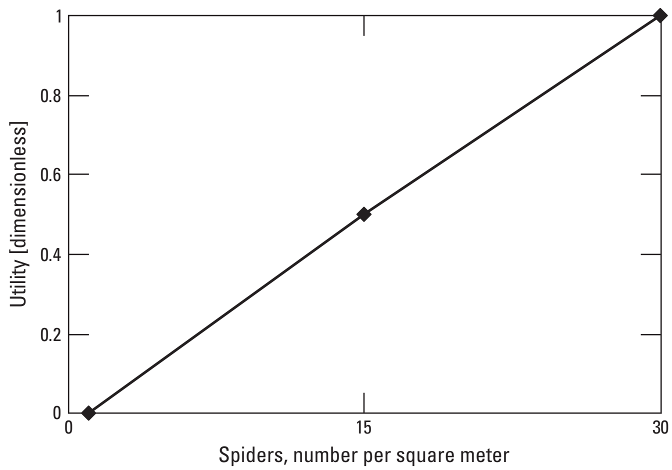


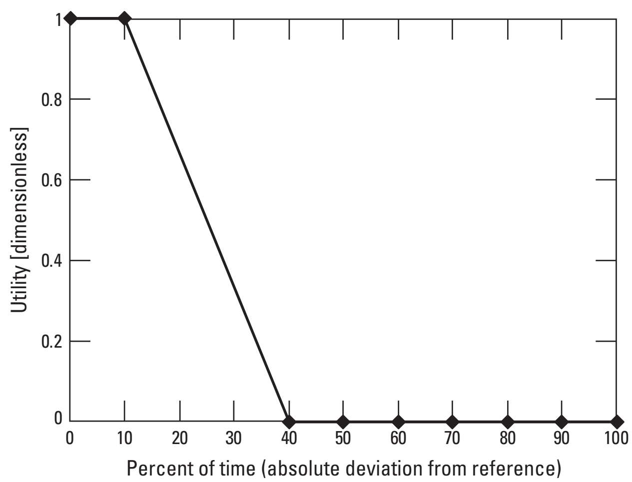
Figure 2.5. American black ducks at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.



If $x \le 15$, then $u(x) = 0.5 \times \frac{x-1}{14}$

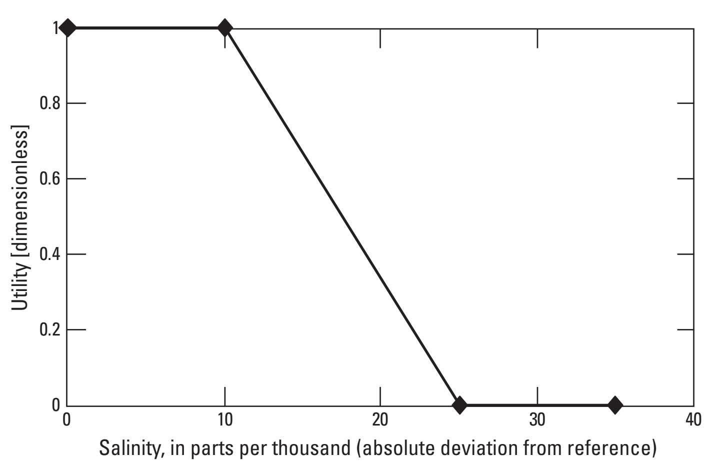
If $x > 15$, then $u(x) = 0.5 + (0.5 \times \frac{x-15}{15})$

Figure 2.6. Marsh spiders at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.



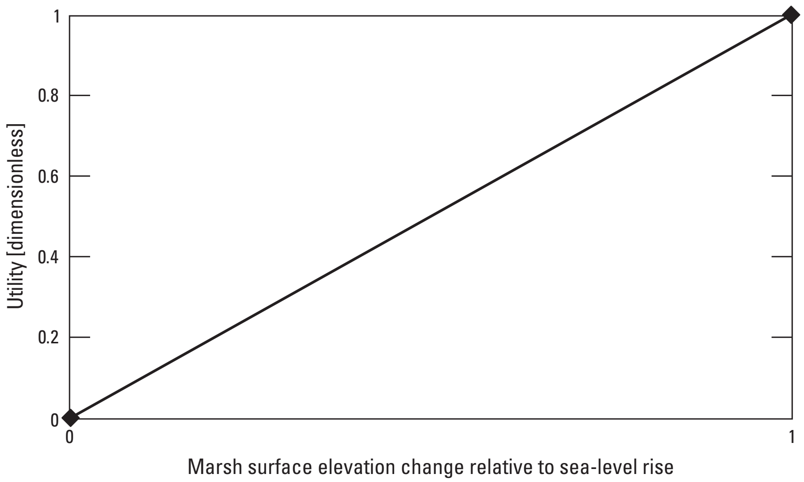
If $x \le 10$, then $u(x) = 1$
If $x \ge 40$, then $u(x) = 0$
If $10 < x < 40$, then $u(x) = 1 - \frac{x-10}{30}$

Figure 2.7. Duration of surface flooding at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.



If $x \le 10$, then $u(x) = 1$
If $x \ge 25$, then $u(x) = 0$
If $10 < x < 25$, then $u(x) = 1 - \frac{x-10}{15}$

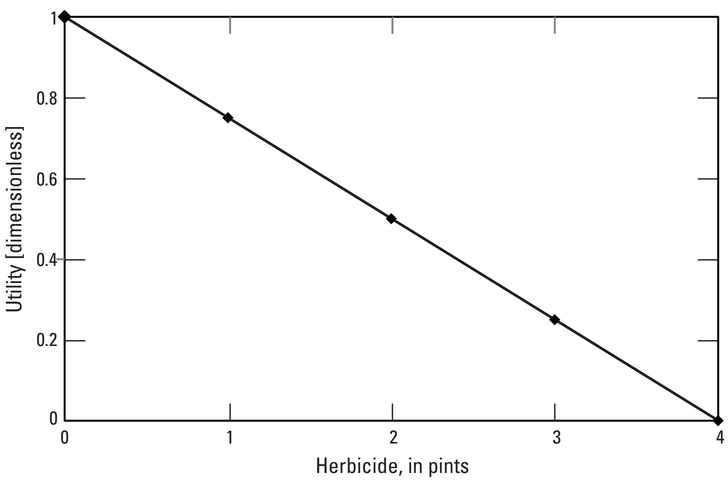
Figure 2.8. Salinity of surface water at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.



$$u(x) = \frac{x - Low}{High - Low}$$

where
Low = 0, lower than sea-level rise
High = 1, above sea-level rise

Figure 2.9. Change in marsh surface elevation relative to sea-level rise at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.



$$u(x) = \frac{High - x}{High - Low}$$

where
Low = 0
High = 4

Figure 2.10. Application of herbicides at the Edwin B. Forsythe National Wildlife Refuge, New Jersey.

Reference Cited

Neckles, H.A., Lyons, J.E., Guntenspergen, G.R., Shriver, W.G., and Adamowicz, S.C., 2015, Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems: Estuaries and Coasts, v. 38, no. 4, p. 1215–1232. [Also available at https://doi.org/10.1007/s12237-014-9822-5.]

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