Optimization of Salt Marsh Management at the Bombay Hook National Wildlife Refuge, Delaware, Through Use of Structured Decision Making

Open-File Report 2018–1160
Version 1.1, May 2019

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

Cover. Photograph showing a salt marsh at the Bombay Hook National Wildlife Refuge in Delaware; photograph courtesy of Tim Williams, used with permission by the U.S. Fish and Wildlife Service.

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By Hilary A. Neckles, James E. Lyons, Jessica L. Nagel, Susan C. Adamowicz, Toni Mikula, Susan T. Guiteras, and Laura R. Mitchell

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
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
ppt	part per thousand
SMU	salt marsh management unit
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 salt marsh management decisions at the Bombay Hook National Wildlife Refuge in Delaware. Refuge biologists, refuge managers, and research scientists identified multiple potential management actions to improve the ecological integrity of eight salt 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 would be accrued from each potential management action. Constrained optimization was used to identify the set of management actions, one per salt marsh management unit, that would 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 would increase consistently up to approximately $300,000, but that further expenditures would yield diminishing return on investment. Management actions selected within optimal portfolios at total costs less than $300,000 included hydrologic restoration, recontouring adjacent uplands to facilitate marsh migration, and burning the marsh. The prototype presented here provides a framework for decision making at the Bombay Hook 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 refuge.

[1]U.S. Geological Survey.

[2]U.S. Fish and Wildlife Service.

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 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).

The Bombay Hook National Wildlife Refuge, in coastal Delaware, protects one of the largest remaining tracts of salt marsh in the mid-Atlantic region (FWS, 2014). The refuge's salt marsh, considered its most valuable habitat (FWS, 2013), has been altered substantially by human activities from colonial to recent times. Historical alterations include

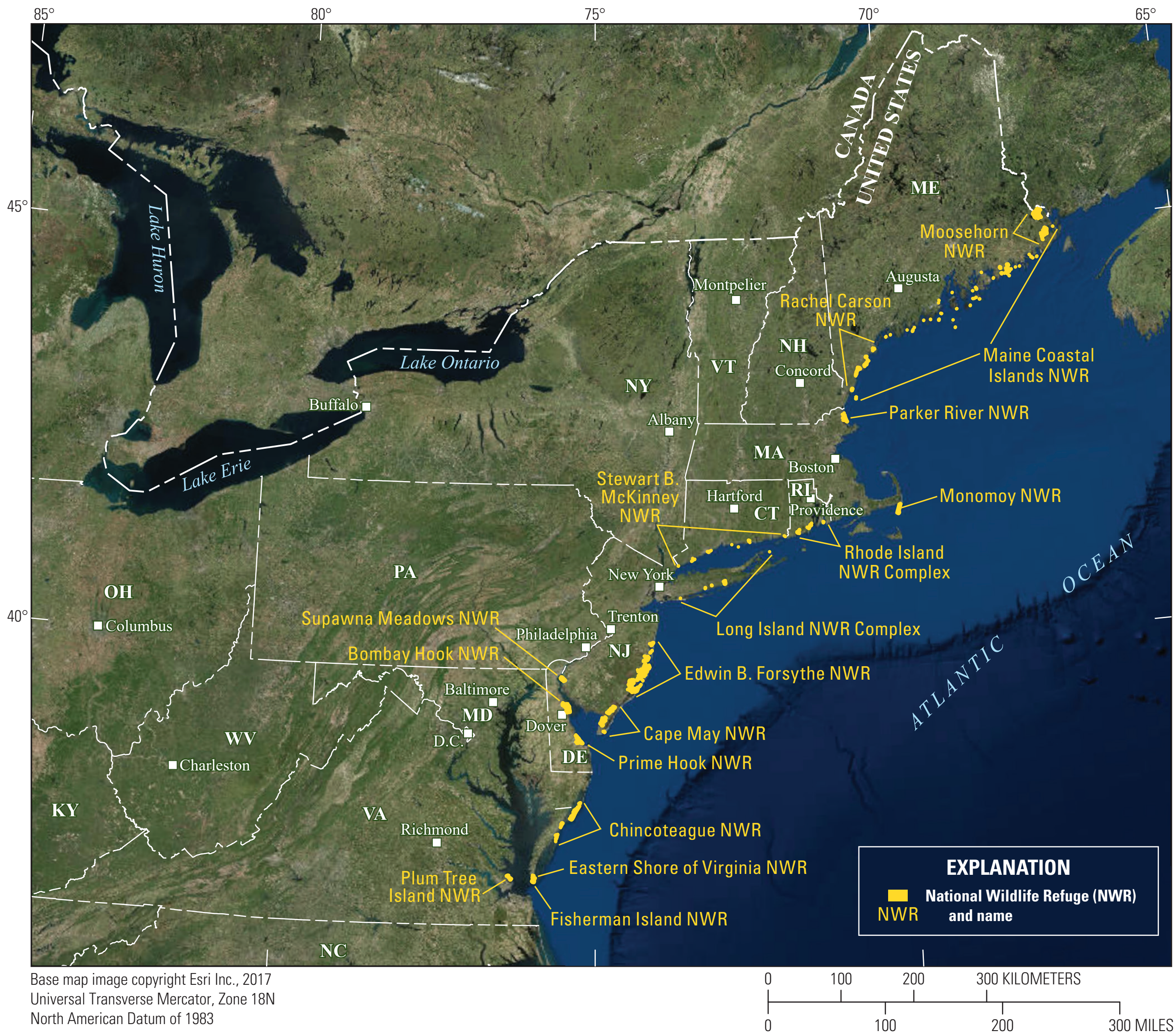

Figure 1. National wildlife refuges and national wildlife refuge complexes of the U.S. Fish and Wildlife Service where salt marsh integrity was assessed from 2012 to 2016 using the regional monitoring protocol.

construction of canals, extensive ditching, and other changes to natural hydrology (FWS, 2016). Some areas of the marsh have been invaded by *Phragmites australis* (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017), and marsh edges bordering Delaware Bay are subject to erosion (FWS, 2016). Primary management concerns are loss of the marsh platform through shoreface erosion coupled with submergence resulting from rising sea level (McDowell, 2017). Refuge managers and biologists are actively engaged in identifying opportunities for possible salt marsh restoration (FWS, 2013). Therefore, 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 Bombay Hook 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 eight salt marsh management units at the refuge (fig. 2), approximate cost estimates 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 Bombay Hook National Wildlife Refuge.

Description of Study Area

The Bombay Hook National Wildlife Refuge is a tidal marsh-dominated system along the Delaware Bay in Kent County, Delaware (fig. 2). About 5,000 hectares of salt marsh is divided into eight salt marsh management units: Leatherberry (SMU–1), Bombay Hook Island North (SMU–2), Georges Island (SMU–3), Bombay Hook Island South (SMU–4), Kent Island (SMU–5), Kelly Island (SMU–6), Steamboat (SMU–7), and Air Force (SMU–8). The managed marsh area is bordered by Delaware Bay to the east and primarily by adjoining marsh land to the south, west, and north, leading to mostly natural surrounding landscapes; however, George’s Island (SMU–3) and Steamboat (SMU–7) do have small areas of agricultural land nearby. None of the salt marsh management units have tidal restrictions, but two (Steamboat [SMU–7] and Air Force [SMU–8]) are heavily ditched. From 2012 to 2014, average surface-water salinities in summer ranged from 13 parts per thousand (ppt) at Bombay Hook Island North (SMU–2) to 17 ppt at Bombay Hook Island South (SMU–4) and George’s Island (SMU–3; S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017).

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 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 within 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

Figure 2. Salt marsh management units at the Bombay Hook National Wildlife Refuge in Delaware.

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 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 into low-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) described development of the structured decision-making framework and a case-study application to Prime Hook National Wildlife Refuge, Delaware, in detail.

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

[Two fundamental objectives (overall goals of the decision problem) draw directly from National Wildlife Refuge System policy to maintain, restore, and enhance biological integrity, diversity, and environmental health within the refuge. These objectives are broken down into low-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 sum to 1. The weight for each metric is the product of the weights from each level of the hierarchy leading to that metric. NA, not applicable]

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):	NA	NA
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 salt 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):	NA	NA
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 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 Bombay Hook 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.

Table 2. Participants in 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 Patuxent Wildlife Research Center	Glenn Guntenspergen
USGS Patuxent Wildlife Research Center	James Lyons
USGS Patuxent Wildlife Research Center	Hilary Neckles

Participants identified a range of possible management actions for achieving objectives within each salt marsh management unit at the Bombay Hook National Wildlife Refuge and estimated the total cost of implementation over 5 years. Potential actions to enhance salt marsh integrity ranged from focused efforts to restore hydrologic connections to large-scale projects to alter marsh elevation or vegetation succession (table 3). Participants predicted the outcomes of each management action 5 years after 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. However, for three metrics lacking assessment data (abundance of American black ducks, density of spiders, and change in marsh surface elevation relative to sea-level rise), baseline conditions were estimated by using expert judgement. 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 response.

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), using regional value functions (app. 2). Weighted utilities were then 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 then used to find the management portfolio (the combination of actions, one action per salt marsh management unit) that would maximize the total management benefit across all units subject to varying cost constraints for the entire the refuge. Constrained optimization was done by using integer linear programming as implemented in the Solver tool in Microsoft Excel (Kirkwood, 1997). Budget constraints were increased in $10,000 increments up to $50,000; in $50,000 increments up to $300,000; in $100,000 increments up to $1 million; and in $500,000 increments thereafter. A cost-benefit plot 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 cost above which further expenditures would yield diminishing returns on investment. To exemplify use of

Table 3. Possible management actions for achieving objectives within salt marsh management units at the Bombay Hook National Wildlife Refuge in Delaware, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.

[SMU, salt marsh management unit; 1 mile=1.609 kilometers]

Management action	Estimated cost over 5 years	Performance metric									
		Native vegetation (percent 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)	Hydrology: Duration of surface flooding, deviation[2] (percent)	Hydrology: Surface-water salinity, deviation[2] (parts per thousand)	Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
Leatherberry (SMU–1)											
A. No action	0	98.67	6.29	11	6.5	Low	1	6.47	0	0	0
B. Block Raymond Gut	50,000	98.67	10	11	7	Medium	1	0.24	0	1	0
C. Living shoreline along south edge of flats	1,875,000	98.67	6.29	11	6.87	Low	1	6.47	0	0	0
D. Living shoreline along south edge of flats with thin layer deposition	2,175,000	98.67	10	11	7	Medium	15	6.47	0	1	0
E. Remove or breach Shearness Pool impoundment dikes and recontour basin	480,000	98.67	15	11	7	Medium	15	6.47	0	1	0
F. Remove or breach Bear Swamp impoundment dikes and recontour basin	390,000	98.67	15	11	7	Medium	15	6.47	0	1	0
G. Recontour adjacent upland and plant to facilitate marsh migration; control *Phragmites australis*	39,750	98.67	6.29	11	6.87	Low	15	6.47	0	1	0
H. Stabilize cuts in bank along Sluice Ditch	100,000	98.67	6.29	11	6.87	Low	15	6.47	0	0	0
Bombay Hook Island North (SMU–2)											
A. No action	0	92.67	47.03	11	6	High	1	59.32	2	0	0
B. Delaware Bay offshore protection; living shoreline	1,132,560	92.67	47.03	11	7.16	High	15	31.76	2	0	0
Georges Island (SMU–3)											
A. No action	0	97.33	42.75	4	7.31	Medium	1	5.04	2	0	0
B. Block Raymond Gut	50,000	97.33	45	5	7.5	Medium	1	3.24	2	1	0
C. Thin layer deposition in marsh interior	893,000	97.33	50	5	7.5	Medium	15	5.04	2	1	0
D. Remove or breach Raymond Pool impoundment dikes and recontour basin	230,000	97.33	50	10	7.5	Medium	15	5.04	2	1	0
E. Restore oxbow hydrology along Leipsic River	100,000	97.33	42.75	4	7.31	Medium	1	2.24	2	0	0
F. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis*	106,000	97.33	50	5	7.5	Medium	15	5.04	2	1	0
G. Stabilize cuts in bank along Leipsic River	100,000	97.33	42.75	4	7.31	Medium	1	5.04	2	0	0
Bombay Hook Island South (SMU–4)											
A. No action	0	87.17	55.63	8	9	High	15	68.93	2	0	0
B. Delaware Bay offshore protection; living shoreline	1,287,000	87.17	55.63	8	9.75	High	15	56.76	2	0	0

Table 3. Possible management actions for achieving objectives within salt marsh management units at the Bombay Hook National Wildlife Refuge in Delaware, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[SMU, salt marsh management unit; 1 mile=1.609 kilometers]

Management action	Estimated cost over 5 years	Performance metric									
		Native vegetation (percent 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)	Hydrology: Duration of surface flooding, deviation[2] (percent)	Hydrology: Surface-water salinity, deviation[2] (parts per thousand)	Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
Kent Island (SMU–5)											
A. No action	0	99.5	85.1	8	9.82	High	1	60.77	0	0	0
B. Restore sinuosity along approximately 1 mile of stream	100,000	99.5	90	9	9.9	High	15	21.76	0	1	0
C. Restore oxbow hydrology along Leipsic River	100,000	99.5	85.1	8	9.82	High	15	1.76	0	1	0
D. Stabilize cuts in bank along Leipsic River	100,000	99.5	85.1	8	9.82	High	1	60.77	0	1	0
Kelly Island (SMU–6)											
A. No action	0	99.5	55.04	7	6	Medium	15	15.9	1	0	0
B. Delaware Bay offshore protection; living shoreline	643,000	99.5	55.04	7	6.15	Medium	15	15.9	1	0	0
Steamboat (SMU–7)											
A. No action	0	91.43	33.65	7	4.1	Low	1	51	1	0	0
B. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis*	132,500	91.43	35	7	4.5	Low	15	51	1	1	0
C. Burn the marsh	50,000	85	40	7	5	Low	1	51	1	1	0
Air Force (SMU–8)											
A. No action	0	98.58	23.09	6	5.16	Low	1	18.05	0	0	0
B. Burn the marsh	50,000	90	30	6	6	Low	1	18.05	0	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, less than sea-level rise; 1, greater than or equal to sea-level rise.

[4]Measures level of herbicide applied: 0, none applied; 1, some applied.

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh management units at the Bombay Hook National Wildlife Refuge in Delaware.

[Numeric table entries are weighted utilities, which were calculated as raw utilities × objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 1). 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 2). The total management benefit for each action is the sum of weighted utilities across all performance metrics. SMU, salt marsh management unit]

Management action	Performance metric										Total management benefit
	Native vegetation	Nekton		Tidal marsh obligate birds	American black ducks	Spider density	Hydrology		Marsh surface elevation change	Herbicide application	
		Density	Species richness				Duration of surface flooding	Surface-water salinity			
Leatherberry (SMU–1)											
A. No action	0.119	0.006	0.045	0.066	0	0	0.11	0.11	0	0.06	0.516
B. Block Raymond Gut	0.119	0.009	0.045	0.071	0.075	0	0.11	0.11	0.22	0.06	0.819
C. Living shoreline along south edge of flats	0.119	0.006	0.045	0.069	0	0	0.11	0.11	0	0.06	0.52
D. Living shoreline along south edge of flats with thin layer deposition	0.119	0.009	0.045	0.071	0.075	0.045	0.11	0.11	0.22	0.06	0.864
E. Remove or breach Shearness Pool impoundment dikes and recontour basin	0.119	0.013	0.045	0.071	0.075	0.045	0.11	0.11	0.22	0.06	0.868
F. Remove or breach Bear Swamp impoundment dikes and recontour basin	0.119	0.013	0.045	0.071	0.075	0.045	0.11	0.11	0.22	0.06	0.868
G. Recontour adjacent upland and plant to facilitate marsh migration; control *Phragmites australis*	0.119	0.006	0.045	0.069	0	0.045	0.11	0.11	0.22	0.06	0.785
H. Stabilize cuts in bank along Sluice Ditch	0.119	0.006	0.045	0.069	0	0.045	0.11	0.11	0	0.06	0.565
Bombay Hook Island North (SMU–2)											
A. No action	0.117	0.031	0.045	0.061	0.1	0	0	0.11	0	0.06	0.524
B. Delaware Bay offshore protection; living shoreline	0.117	0.031	0.045	0.072	0.1	0.045	0.03	0.11	0	0.06	0.611
Georges Island (SMU–3)											
A. No action	0.119	0.03	0.016	0.074	0.075	0	0.11	0.11	0	0.06	0.594
B. Block Raymond Gut	0.119	0.031	0.02	0.076	0.075	0	0.11	0.11	0.22	0.06	0.821
C. Thin layer deposition in marsh interior	0.119	0.033	0.02	0.076	0.075	0.045	0.11	0.11	0.22	0.06	0.868
D. Remove or breach Raymond Pool impoundment dikes and recontour basin	0.119	0.033	0.041	0.076	0.075	0.045	0.11	0.11	0.22	0.06	0.888
E. Restore oxbow hydrology along Leipsic River	0.119	0.03	0.016	0.074	0.075	0	0.11	0.11	0	0.06	0.594
F. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis*	0.119	0.033	0.02	0.076	0.075	0.045	0.11	0.11	0.22	0.06	0.868
G. Stabilize cuts in bank along Leipsic River	0.119	0.03	0.016	0.074	0.075	0	0.11	0.11	0	0.06	0.594

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh management units at the Bombay Hook National Wildlife Refuge in Delaware.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities × objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 1). 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 2). The total management benefit for each action is the sum of weighted utilities across all performance metrics. SMU, salt marsh management unit]

Management action	Performance metric										Total management benefit
	Native vegetation	Nekton		Tidal marsh obligate birds	American black ducks	Spider density	Hydrology		Marsh surface elevation change	Herbicide application	
		Density	Species richness				Duration of surface flooding	Surface-water salinity			
Bombay Hook Island South (SMU–4)											
A. No action	0.115	0.035	0.033	0.091	0.1	0.045	0	0.11	0	0.06	0.588
B. Delaware Bay offshore protection; living shoreline	0.115	0.035	0.033	0.098	0.1	0.045	0	0.11	0	0.06	0.596
Kent Island (SMU–5)											
A. No action	0.12	0.044	0.033	0.099	0.1	0	0	0.11	0	0.06	0.566
B. Restore sinuosity along approximately 1 mile of stream	0.12	0.045	0.037	0.1	0.1	0.045	0.067	0.11	0.22	0.06	0.904
C. Restore oxbow hydrology along Leipsic River	0.12	0.044	0.033	0.099	0.1	0.045	0.11	0.11	0.22	0.06	0.941
D. Stabilize cuts in bank along Leipsic River	0.12	0.044	0.033	0.099	0.1	0	0	0.11	0.22	0.06	0.786
Kelly Island (SMU–6)											
A. No action	0.12	0.035	0.029	0.061	0.075	0.045	0.088	0.11	0	0.06	0.622
B. Delaware Bay offshore protection; living shoreline	0.12	0.035	0.029	0.062	0.075	0.045	0.088	0.11	0	0.06	0.624
Steamboat (SMU–7)											
A. No action	0.116	0.025	0.029	0.041	0	0	0	0.11	0	0.06	0.381
B. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis*	0.116	0.026	0.029	0.045	0	0.045	0	0.11	0.22	0.06	0.651
C. Burn the marsh	0.113	0.028	0.029	0.051	0	0	0	0.11	0.22	0.06	0.611
Air Force (SMU–8)											
A. No action	0.119	0.019	0.025	0.052	0	0	0.08	0.11	0	0.06	0.465
B. Burn the marsh	0.116	0.023	0.025	0.061	0	0	0.08	0.11	0.22	0.06	0.694

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

Management actions identified to improve marsh integrity at the Bombay Hook National Wildlife Refuge included strategies to restore or enhance physical marsh features, protect shorelines from erosion, and manage native marsh vegetation (table 3). Within individual management units, for costs ranging from $0 to $2.175 million, the estimated management benefits for specific actions across all metrics (measured as weighted utilities) ranged from 0.381 to 0.941 (tables 3 and 4). Within each unit, the action with both the lowest management benefit and lowest cost was the no-action option (action A).

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 any unit) to approximately $4 million, the total management benefit increased from 4.277 to 5.873 (table 5). Graphical analysis showed a consistent increase in management benefit as costs increased to $300,000 (fig. 3, portfolio 8). Expenditures beyond this amount would yield diminishing returns on investment, and portfolio 12, at a total cost of about $800,000, dominated the costlier portfolios in terms of cost-benefit tradeoffs (fig. 3).

Several patterns emerged relative to management actions selected for yielding the best returns on investments within the optimal set of portfolios (table 5, portfolios 2 through 8). At Leatherberry (SMU–1) and Georges Island (SMU–3), the optimal portfolios consistently included either blocking a

Table 5. Actions included in various management portfolios to maximize the total management benefits subject to increasing cost constraints in the Bombay Hook National Wildlife Refuge in Delaware.

[Letter designations for actions refer to specific actions and are listed in tables 3 and 4. Portfolios represent the combination of actions, one per salt marsh management unit, that maximized the total management benefit across all units subject to a refugewide cost constraint. The management actions constituting individual portfolios were selected using constrained optimization. SMU, salt marsh management unit]

Portfolio	Salt marsh management unit								Total cost (dollars)	Total management benefit
	Leatherberry (SMU–1)	Bombay Hook Island North (SMU–2)	Georges Island (SMU–3)	Bombay Hook Island South (SMU–4)	Kent Island (SMU–5)	Kelly Island (SMU–6)	Steamboat (SMU–7)	Air Force (SMU–8)		
1	A	A	A	A	A	A	A	A	0	4.277
2	G	A	A	A	A	A	A	A	39,750	4.525
3	B	A	A	A	A	A	A	A	50,000	4.559
4	B	A	A	A	A	A	C	A	100,000	4.789
5	B	A	A	A	A	A	C	B	150,000	5.018
6	B	A	B	A	A	A	C	B	200,000	5.245
7	B	A	A	A	C	A	C	B	250,000	5.393
8	B	A	B	A	C	A	C	B	300,000	5.620
9	B	A	F	A	C	A	C	B	356,000	5.667
10	B	A	F	A	C	A	B	B	438,500	5.708
11	B	A	D	A	C	A	B	B	562,500	5.728
12	F	A	F	A	C	A	B	B	778,500	5.756
13	E	A	F	A	C	A	B	B	868,500	5.756
14	F	A	D	A	C	A	B	B	902,500	5.777
15	F	B	F	A	C	A	B	B	1,911,060	5.843
16	F	B	D	A	C	A	B	B	2,035,060	5.864
17	E	B	D	A	C	B	B	B	2,768,060	5.865
18	E	B	D	B	C	A	B	B	3,412,060	5.871
19	F	B	D	B	C	B	B	B	3,965,060	5.873
20	E	B	D	B	C	B	B	B	4,055,060	5.873

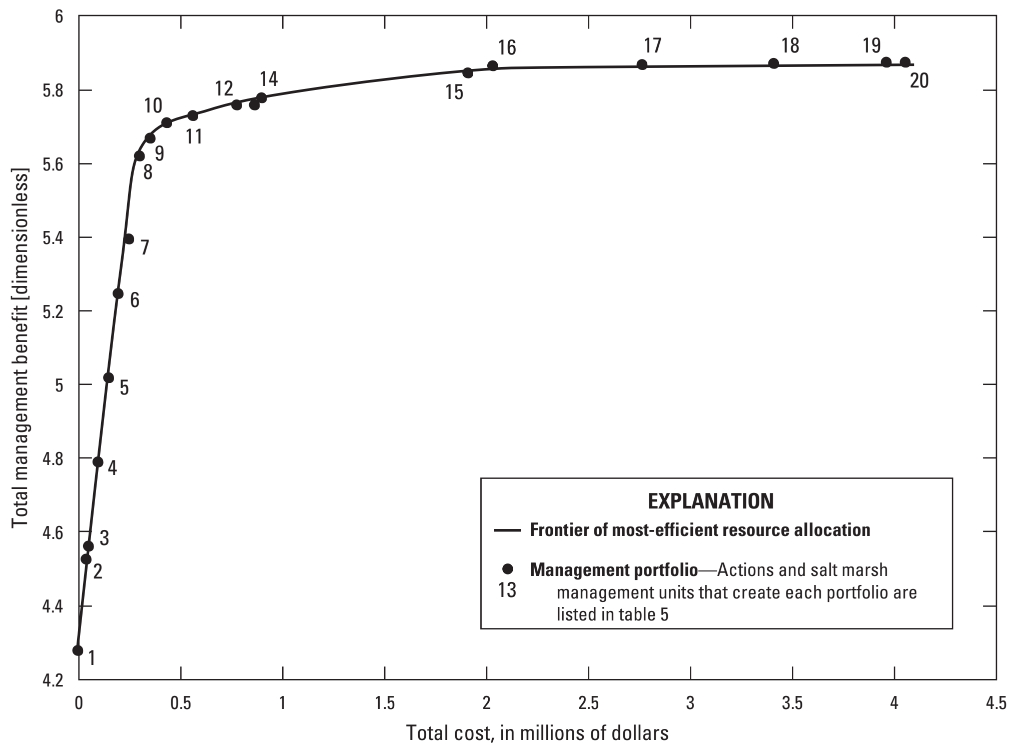

Figure 3. Predicted total management benefit of various portfolios, expressed as weighted utilities, relative to total annual cost at the Bombay Hook National Wildlife Refuge in Delaware. Each portfolio (dot with number) represents a combination of eight management actions, one per salt marsh management unit, as identified in table 5. The line represents the efficient frontier for resource allocation.

manmade waterway (Raymond Gut) or recontouring the adjacent upland and planting to facilitate marsh migration. At three units (Bombay Hook Island North [SMU–2], Bombay Hook Island South [SMU–4], and Kelly Island [SMU–6]), taking no action was preferable to the high expenditures ($643,000 to $1.287 million) and relatively low increases in management benefit (0.002 to 0.087) associated with installation of offshore protection or living shorelines (shorelines that use plants or other natural elements to stabilize estuarine coasts, bays, or tributaries) in Delaware Bay. For other units, actions related to restoring oxbow hydrology along the Leipsic River (Kent Island [SMU–5]), recontouring adjacent upland areas and planting to facilitate marsh migration (Steamboat [SMU–7]), and burning the marsh (Steamboat [SMU–7] and Air Force [SMU–8]) were consistently selected. In contrast, some management actions were never included in an optimal portfolio. For example, although bank stabilization was identified to reduce the effect of erosion on marsh edges within three units (Leatherberry [SMU–1], Georges Island [SMU–3], and Kent Island [SMU–5]), this action was never selected. Similarly, the optimal portfolios never included actions that incorporated thin layer deposition (possible actions within Leatherberry [SMU–1] and Georges Island [SMU–3]).

Examination of constrained optimization results in terms of individual performance metrics reveals the relative effects of implementing a certain portfolio on specific management objectives at the refuge scale. For example, implementing portfolio 8 would be predicted to yield modest gains in management benefits for some metrics, but would yield great gains in the capacity of marsh elevation to keep pace with sea-level rise (fig. 4). Ecologically, the combination of actions in this portfolio would result in an average 14-percent increase in nekton density (averaged across all units), an average 6-percent increase in tidal marsh obligate bird counts, an average 1-percent decrease in native vegetation cover, and an increased capacity for marsh elevation to keep pace with sea-level rise in five of the eight management units (derived as the average difference between the predicted metric scores for the actions implemented in portfolio 8 and the no action alternative, using scores listed in table 3).

Considerations for Optimizing Salt Marsh Management

A regional structured decision-making framework for salt marshes at 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 Bombay Hook 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.

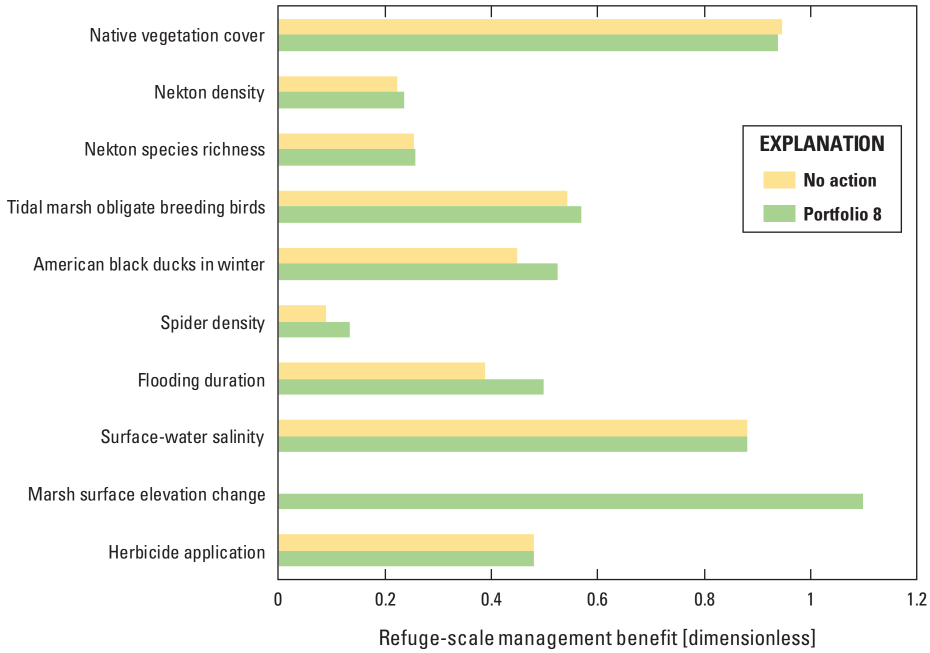

Figure 4. Predicted management benefit at the refuge scale for individual performance metrics, expressed as weighted utilities, resulting from implementation of the management actions included in portfolio 8, in comparison to the management benefit from the baseline "no-action" portfolio at the Bombay Hook National Wildlife Refuge in Delaware. The actions included in each portfolio are listed in table 5.

The suite of potential management actions and predicted outcomes included in this prototype (table 3) were based on current understanding of the Bombay Hook National Wildlife Refuge salt marshes and hypothesized process-response pathways (app. 1). 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 (Kirwan and Megonigal, 2013; Roman, 2017). Results of ongoing hydrodynamic modeling at the Bombay Hook National Wildlife Refuge could be expected to influence the types of management actions considered to enhance marsh sustainability, as well as the predicted responses to management interventions. In addition, during construction of the regional decision model, lack of widely available data on rates of vertical marsh growth led to the adoption of a coarse scale of measurement for change in marsh surface elevation relative to sea-level rise (table 1). Therefore, recent data on salt marsh accretion and elevation change at the Bombay Hook National Wildlife Refuge (McDowell, 2017) could also improve management predictions.

Results of constrained optimizations (table 5) based on the objectives, management actions, and predicted outcomes included in this prototype indicate possible areas for future consideration. For example, thin-layer deposition of dredged sediments on the marsh surface is increasingly proposed to enhance sustainability of northeastern salt marshes (Wigand and others, 2017), but this management action was never included in an optimal portfolio. Multiple, interacting factors influence the long-term success of sediment additions in prolonging marsh integrity, and coastal managers are currently [2018] evaluating the efficacy as a management strategy (Roman, 2017). Increased scientific understanding of conditions under which thin-layer deposition enhances marsh resilience will likely improve management predictions. Secondly, although marsh loss through shore-face erosion is a predominant management concern at the Bombay Hook National Wildlife Refuge, bank stabilization typically had a small effect on the predicted total management benefit over the no-action alternative (table 3, Leatherberry [SMU–1] and Georges Island [SMU–3]) and was not included in any optimal portfolio. This result may lead decision makers to consider deconstructing the objective on maintaining the extent of the marsh platform into subobjectives and performance metrics related to both horizonal and vertical gains and losses. Finally, the constrained optimizations performed here were based on approximations of management costs. As salt marsh management is implemented around the region a list of actual expenses can be compiled, so that future iterations of the decision model can include more accurate cost estimates.

The prototype model for the Bombay Hook National Wildlife Refuge is 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 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 Bombay Hook National Wildlife Refuge is based on a hierarchy of regional objectives and regional value functions relating performance metrics to perceived management benefits. 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 salt marsh management units are included in optimal management portfolios, to further tailor the model to refuge-specific needs.

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Appendixes 1–2

Appendix 1. Regional Influence Diagrams

The influence diagrams (following the style of prototype diagrams in Neckles and others, 2015) in this appendix 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.

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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.]

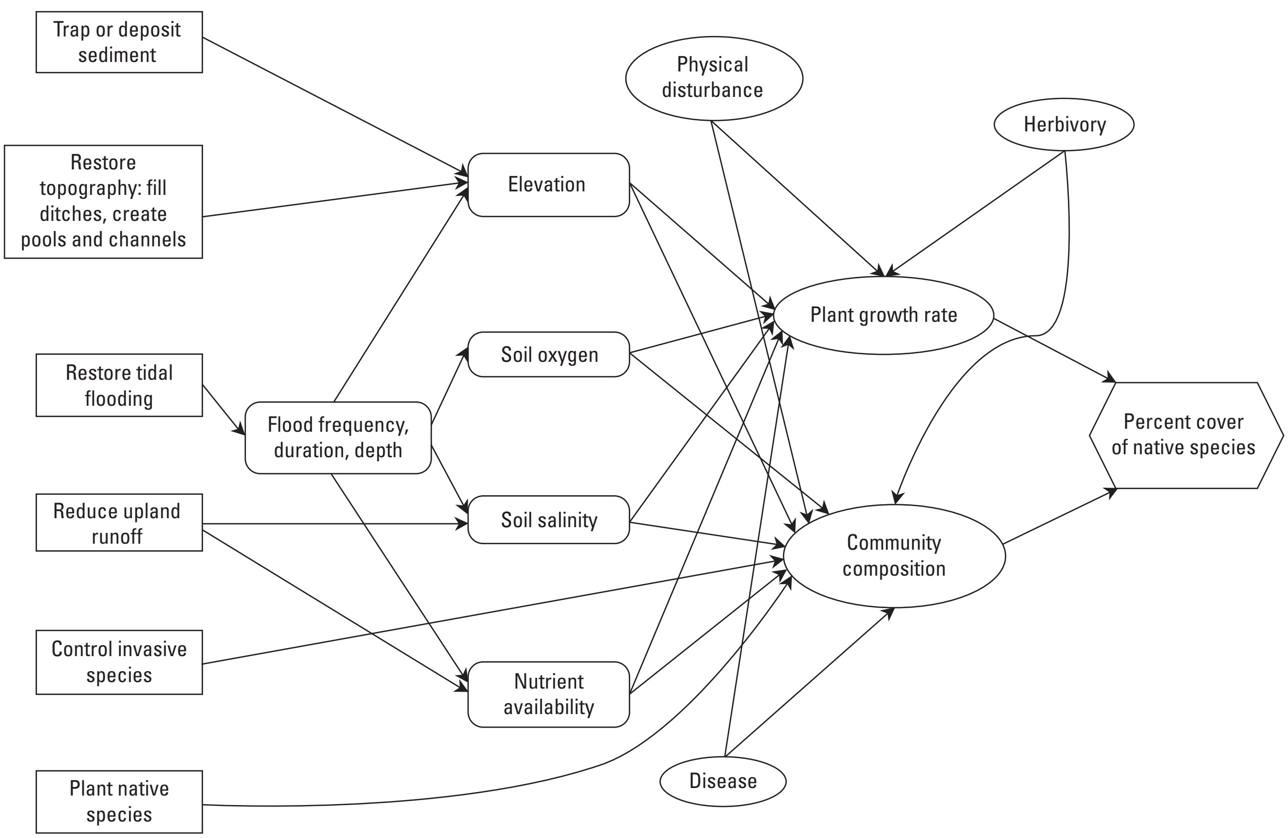

Figure 1.1. Influence diagram used to estimate percent cover of native vegetation in response to implementing certain management actions.

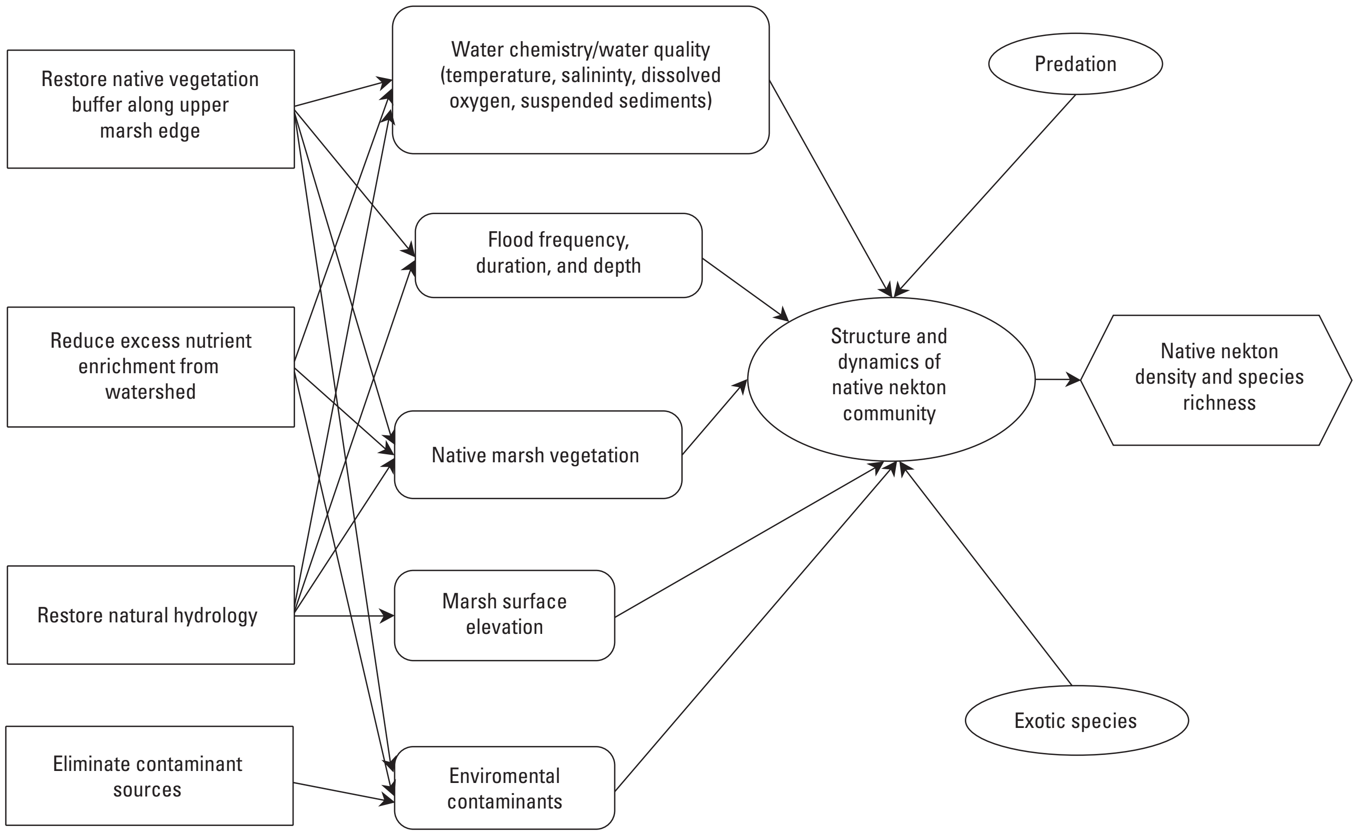

Figure 1.2. Influence diagram used to estimate nekton density and species richness in response to implementing certain management actions.

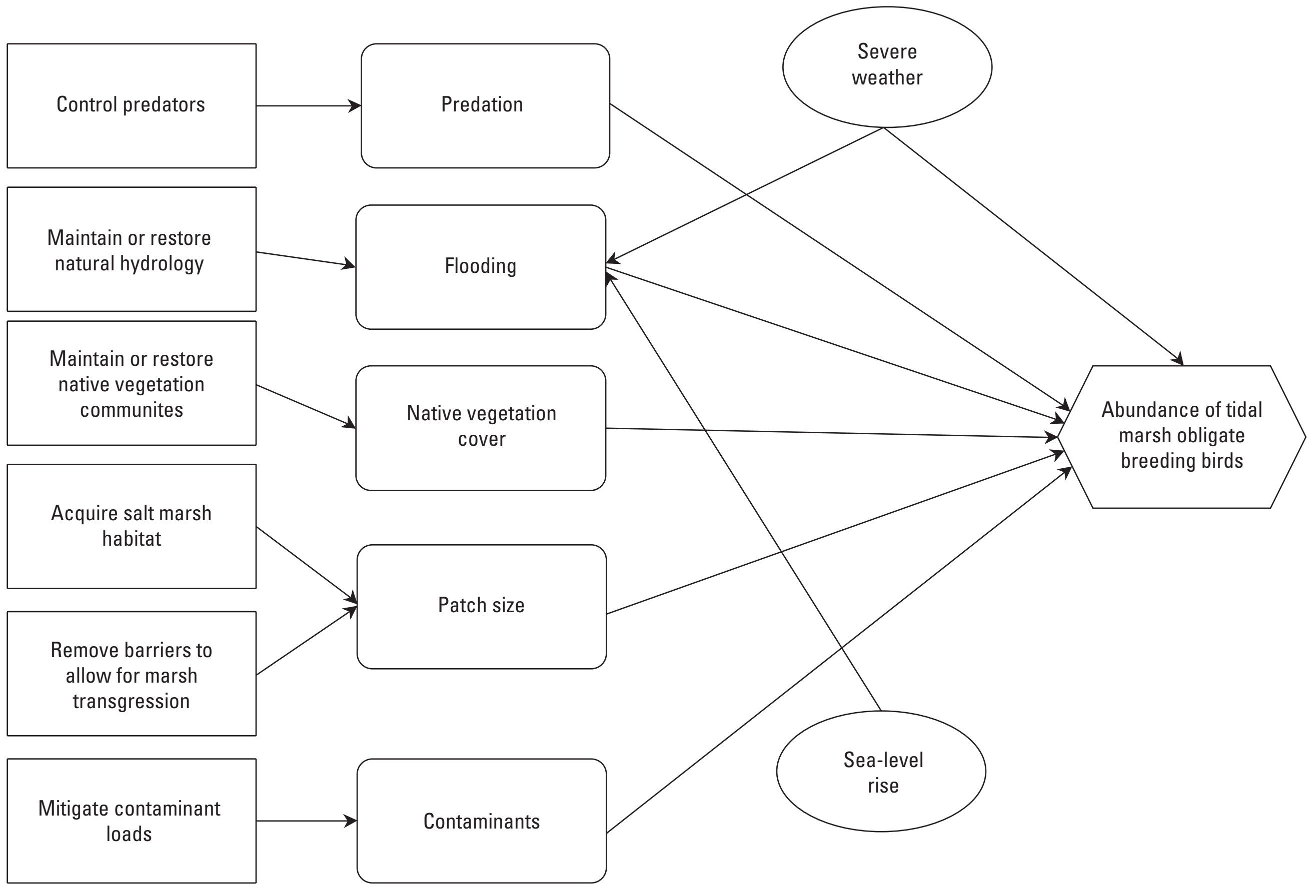

Figure 1.3. Influence diagram used to estimate abundance of tidal marsh obligate breeding birds in response to implementing certain management actions.

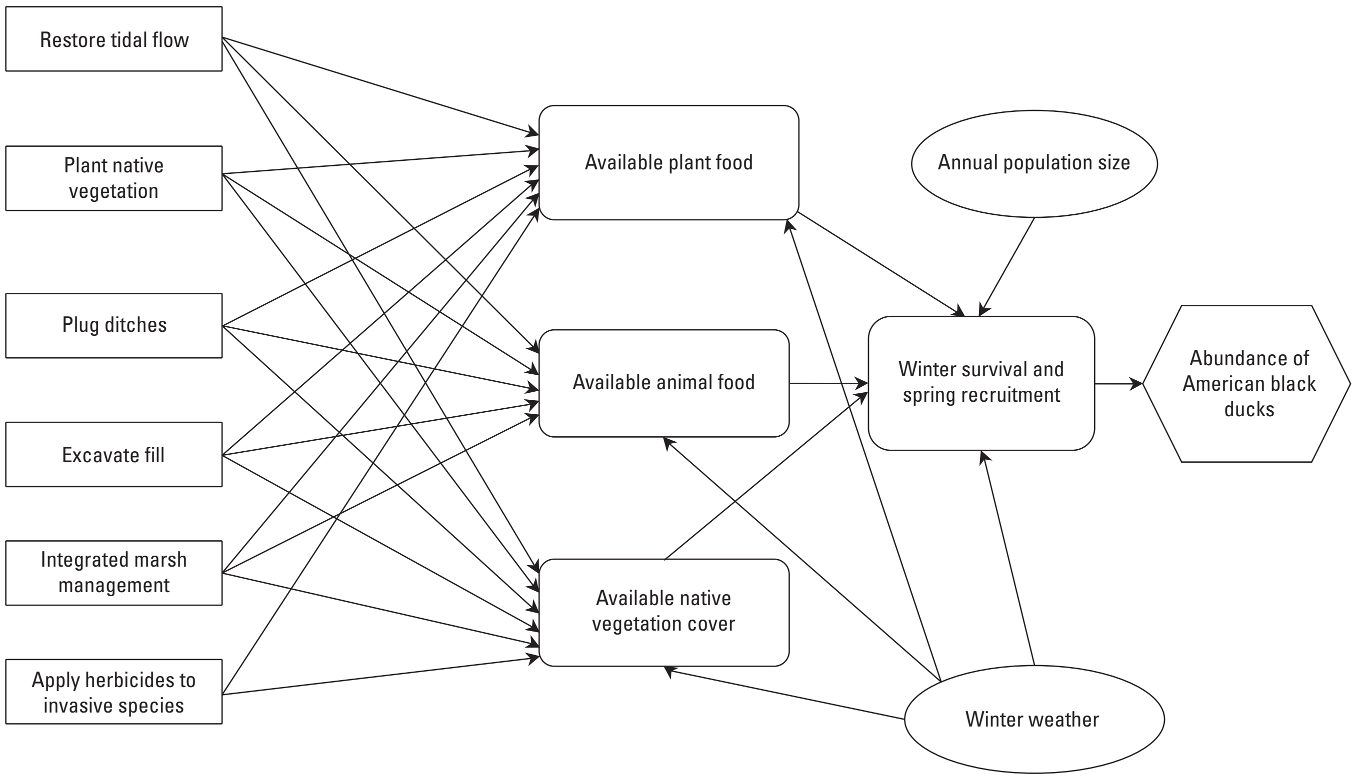

Figure 1.4. Influence diagram used to estimate abundance of American black ducks in winter, as indicator species for nonbreeding wetland birds, in response to implementing certain management actions.

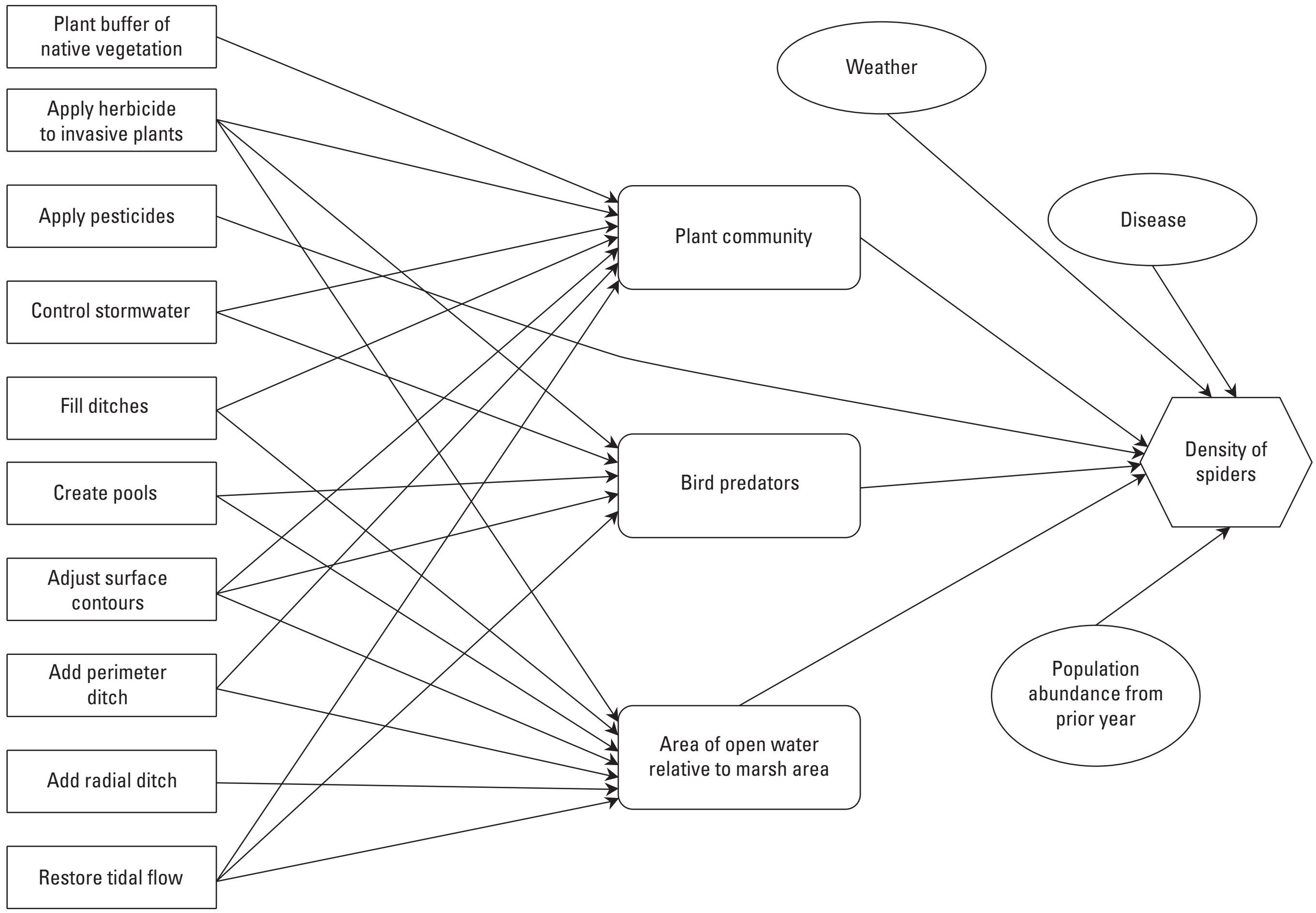

Figure 1.5. Influence diagram used to estimate density of spiders, as indicator of trophic health, in response to implementing certain management actions.

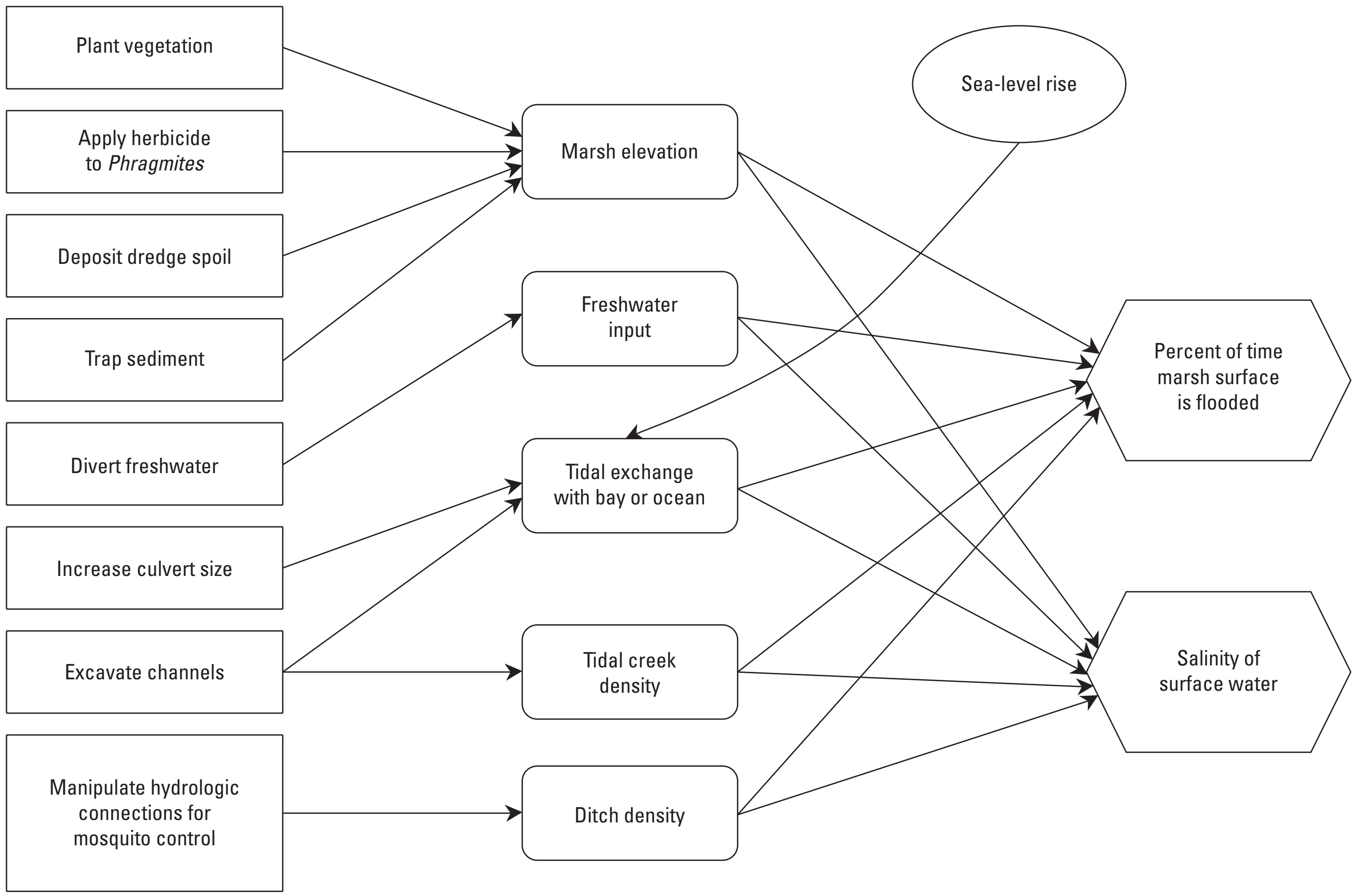

Figure 1.6. Influence diagram used to estimate percent of time marsh surface is flooded and salinity of marsh surface water in response to implementing certain management actions.

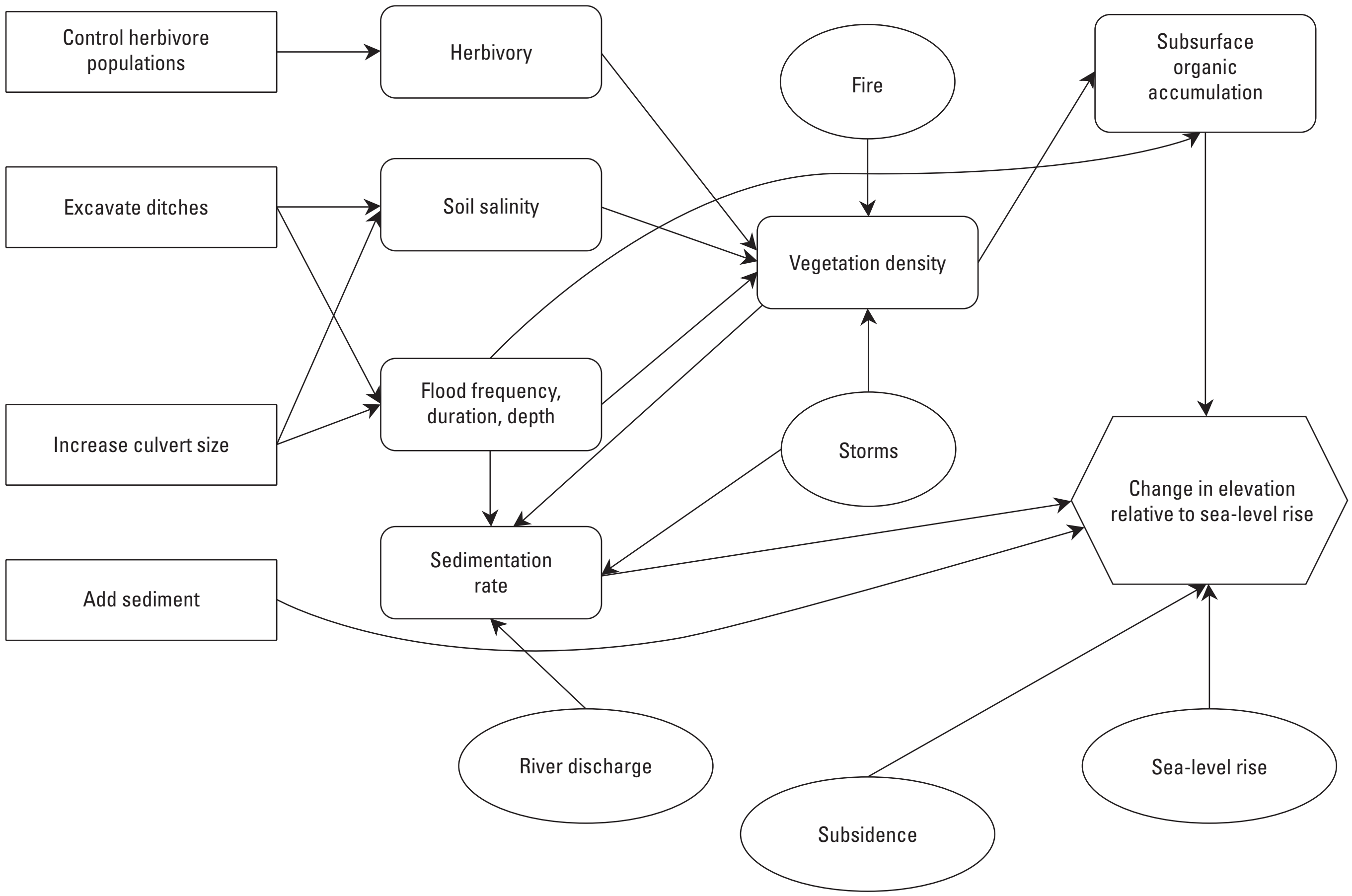

Figure 1.7. Influence diagram used to estimate change in elevation of the marsh surface relative to sea-level rise in response to implementing certain management actions.

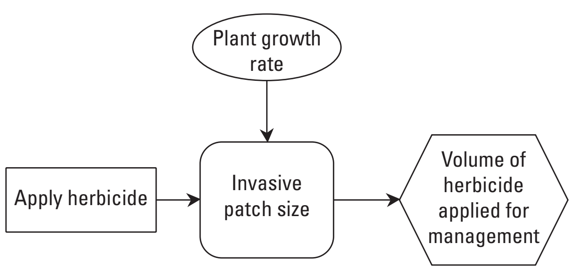

Figure 1.8. Influence diagram used to estimate volume of herbicide that would be applied if decision was made to use chemical control for removing unwanted vegetation.

Appendix 2. Utility Functions for the Bombay Hook 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 below, x, *Low*, *High*, and ρ are expressed in performance metric units; *Low* and *High* represent the endpoints of the given metric range for the Bombay Hook 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.

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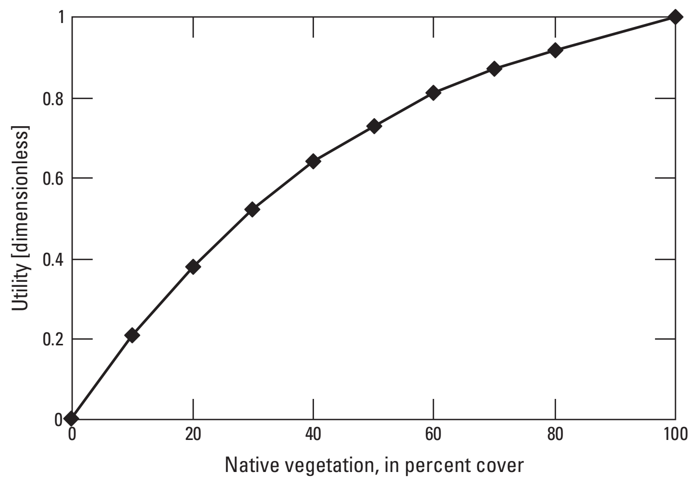
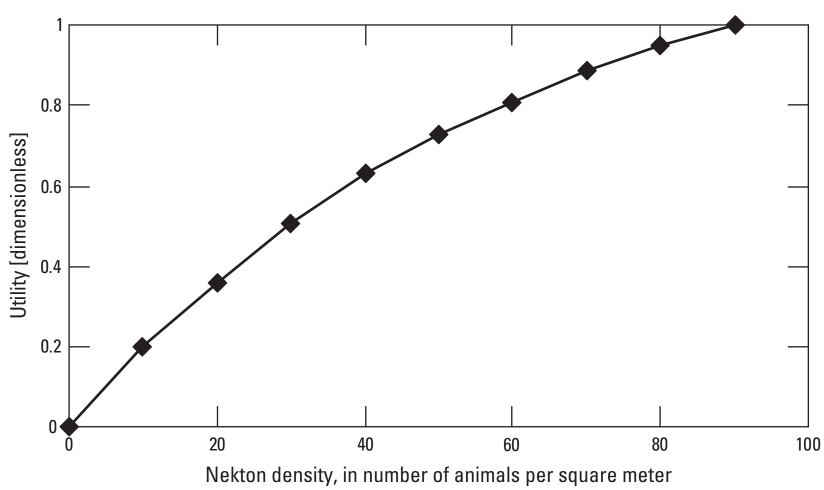
Neckles, H.A., Lyons, J.E., Guntenspergen, G.R., Shriver, W.G., and Adamowicz, S.C., 2015, Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems: Estuaries and Coasts, v. 38, no. 4, p. 1215–1232. [Also available at https://doi.org/10.1007/s12237-014-9822-5.]



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

where
Low = 0
High = 100
ρ = 50

Figure 2.1. Native vegetation at the Bombay Hook National Wildlife Refuge, Delaware.



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

where
Low = 0
High = 90
ρ = 60

Figure 2.2. Native Nekton density at the Bombay Hook National Wildlife Refuge, Delaware.

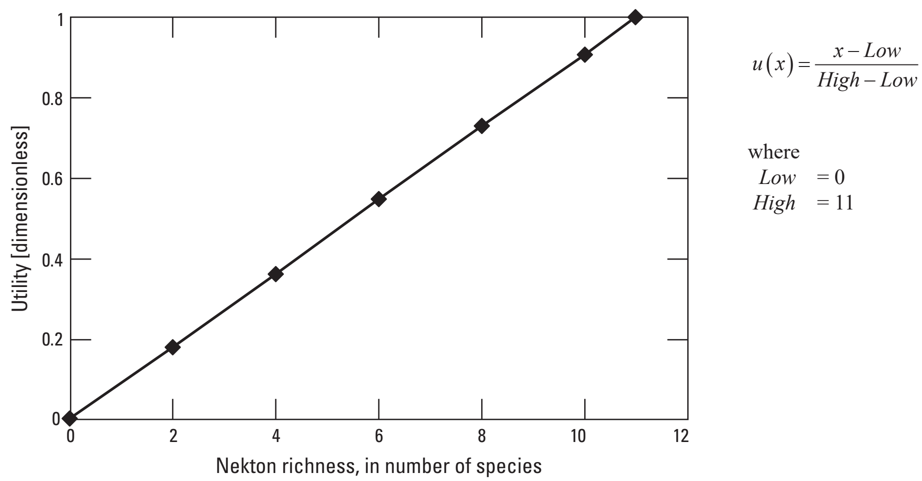


Figure 2.3. Native Nekton species richness at the Bombay Hook National Wildlife Refuge, Delaware.

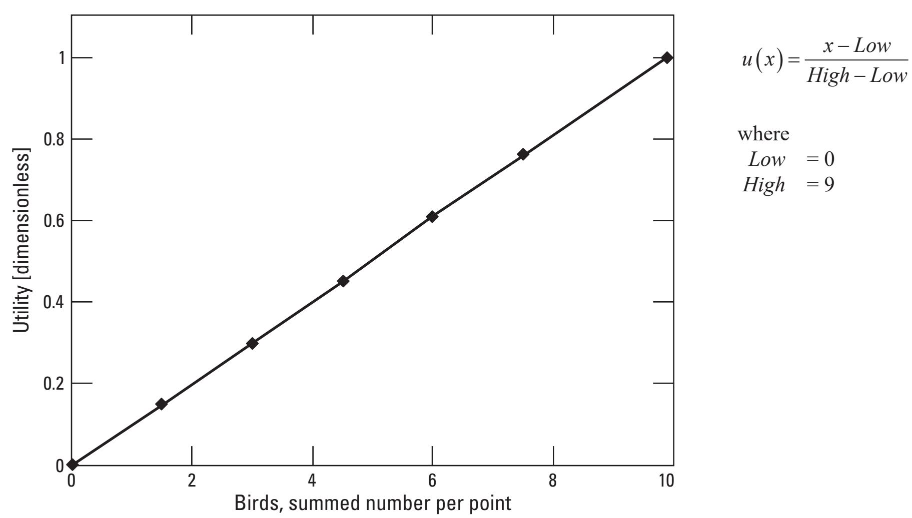
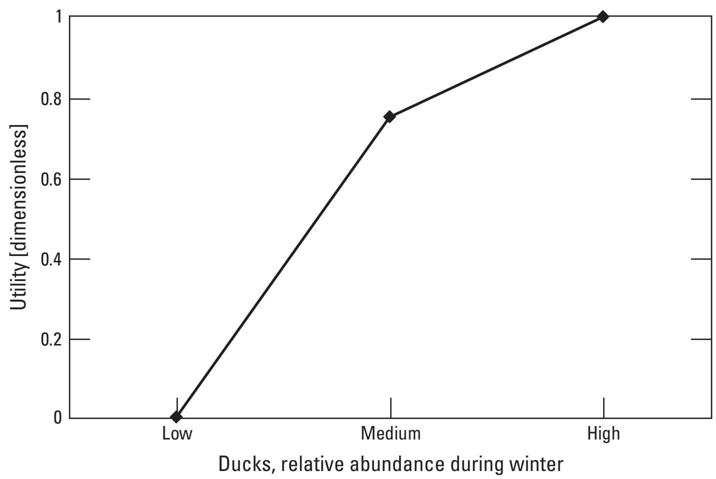
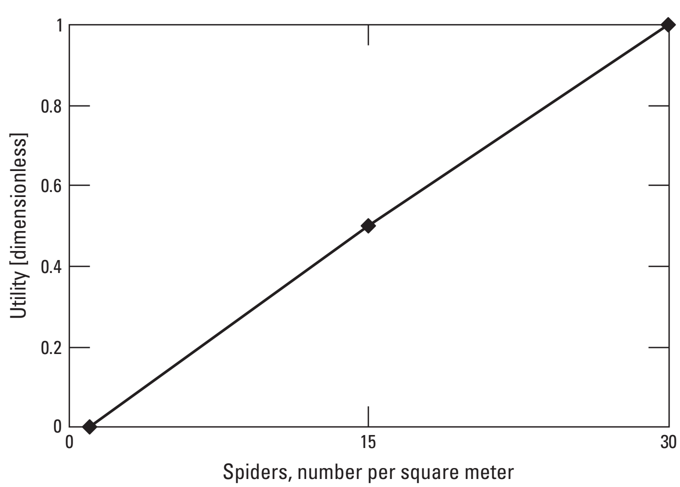


Figure 2.4. Tidal marsh obligate birds at the Bombay Hook National Wildlife Refuge, Delaware.



If $x = Low$, then $u(x) = 0$
If $x = Medium$, then $u(x) = 0.75$
If $x = High$, then $u(x) = 1$

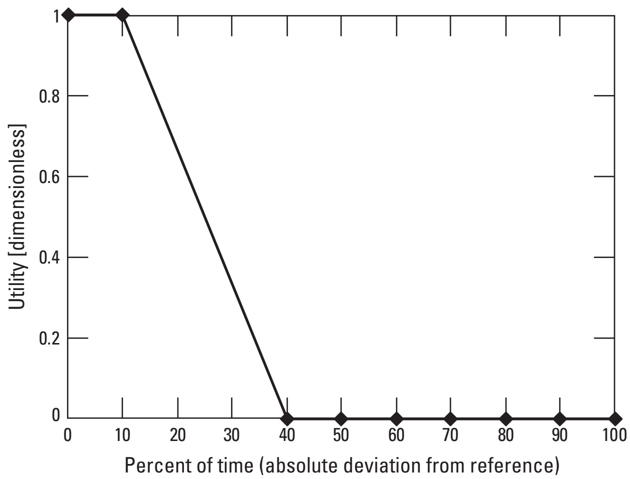
Figure 2.5. American black ducks at the Bombay Hook National Wildlife Refuge, Delaware.



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

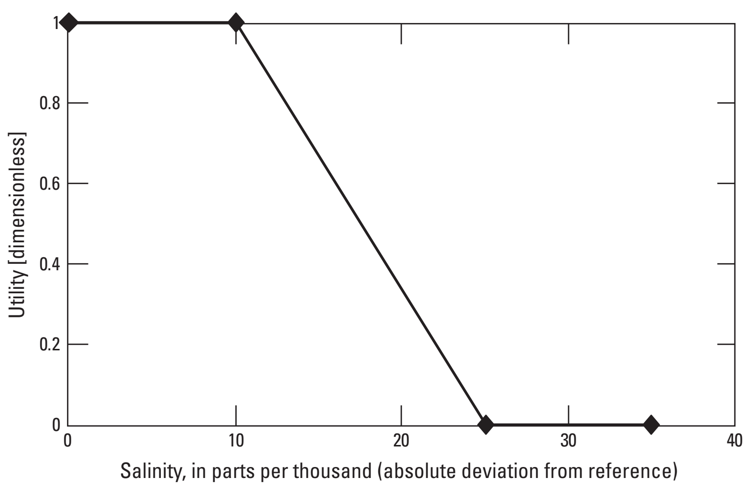
If $x > 15$, then $u(x) = 0.5 + (0.5 \times \frac{x-15}{15})$

Figure 2.6. Marsh spiders at the Bombay Hook National Wildlife Refuge, Delaware.



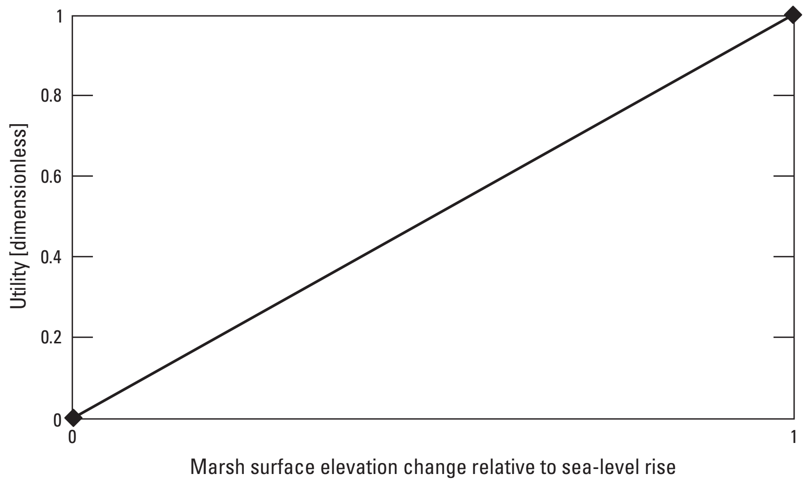
If $x \leq 10$, then $u(x) = 1$
If $x \geq 40$, then $u(x) = 0$
If $10 < x < 40$, then $u(x) = 1 - \frac{x-10}{30}$

Figure 2.7. Duration of surface flooding at the Bombay Hook National Wildlife Refuge, Delaware.



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

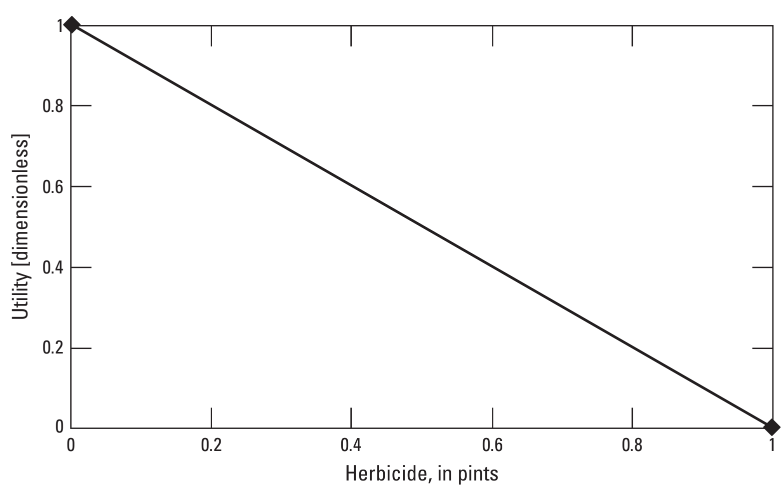
Figure 2.8. Salinity of surface water at the Bombay Hook National Wildlife Refuge, Delaware.



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

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 Bombay Hook National Wildlife Refuge, Delaware.



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

where
Low = 0
High = 1

Figure 2.10. Application of herbicides at the Bombay Hook National Wildlife Refuge, Delaware.

For more information, contact:
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