Optimization of Tidal Marsh Management at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey, Through Use of Structured Decision Making

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

Cover. Photograph of salt marsh habitat at Cape May National Wildlife Refuge along the Cedar Swamp Creek in Petersburg, 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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DAVID BERNHARDT, Secretary

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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
ppt	part per thousand
USGS	U.S. Geological Survey

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By Hilary A. Neckles,[1] James E. Lyons,[1] Jessica L. Nagel,[1] Susan C. Adamowicz,[2] Toni Mikula,[2] Brian Braudis,[2] and Heidi Hanlon[2]

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 Cape May and Supawna Meadows National Wildlife Refuges in New Jersey. Refuge biologists, refuge managers, and research scientists identified multiple potential management actions to improve the ecological integrity of 13 marsh management units within the refuges 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 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 may increase consistently up to approximately $785,000, but that further expenditures may yield diminishing return on investment. Management actions in optimal portfolios at total costs less than $785,000 included applying sediment to the marsh surface (thin layer deposition) in seven marsh management units, controlling the invasive reed *Phragmites australis* in four marsh management units, remediating hydrologic alterations in two marsh management units, and planting native vegetation in one marsh management unit. The management benefits were derived from expected improvements in the capacity for marsh elevation to keep pace with sea-level rise, increases in numbers of spiders (as an indicator of trophic health) and tidal marsh obligate birds, and increased cover of native vegetation. The prototype presented here provides a framework for decision making at the Cape May and Supawna Meadows National Wildlife Refuges 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 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

[1]U.S. Geological Survey.

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

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 Cape May National Wildlife Refuge protects nearly 932 hectares (ha) of salt marsh on the New Jersey coast between Delaware Bay and the Atlantic Ocean (fig. 2). The Supawna Meadows National Wildlife Refuge protects an additional 993 ha of brackish marsh in nearby Pennsville Township, New Jersey (fig. 3). The Supawna Meadows National Wildlife Refuge is managed as a satellite unit of the Cape May National Wildlife Refuge and is included with the Cape May National Wildlife Refuge (collectively referred to as "the refuge" in this report) for descriptive and management purposes. The marsh on each NWR provides critical nesting, migratory, and wintering habitat for birds of highest conservation priority, including saltmarsh sparrows, American oystercatchers, and American black ducks, in the U.S. North American Bird Conservation Initiative's bird conservation region for the New England and mid-Atlantic coast (FWS, 2004, 2011; Steinkamp, 2008; Association of Fish and Wildlife Agencies, 2019). The primary threats to this habitat are marsh submergence associated with rising sea level, further expansion of the invasive reed *Phragmites australis* (hereafter referred to as *Phragmites*), and erosion (FWS, 2004, 2011). Marsh management goals for the refuge focus on maintaining high-quality habitat for breeding, migrating, and wintering birds and restoring and enhancing habitat. Therefore, in this study, the regional structured decision-making framework was used to help prioritize tidal 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 Cape May and Supawna Meadows National Wildlife Refuges. 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 13 marsh management units at the refuge (figs. 2 and 3), 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 Cape May and Supawna Meadows National Wildlife Refuges.

Description of Study Area

The Cape May and Supawna Meadows National Wildlife Refuges are tidal marsh-dominated systems along the southern New Jersey coast. The marsh is divided into 11 marsh management units within the Cape May National Wildlife Refuge (Bidwell Headwaters, Cedar Swamp Creek, Cedar Swamp Headwaters, Del Haven, Dennis Creek, Dias Creek, Dias Headwaters, Green Creek, Reeds Beach, Sunray, Two Mile Beach Unit; fig. 2) and two tidal marsh management units within the Supawna Meadows National Wildlife Refuge (Baldridge Creek and Mud Creek; fig. 3). Most of the land immediately surrounding the marsh management units consists of natural land uses classified within the 2011 National Land Cover Database as categories other than agricultural or developed (MRLC, 2020; S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017), although areas of human development border parts of several marsh management units (Del Haven, Sunray, Two Mile Beach Unit). Many of the marsh management units have tidal restrictions and thus are only moderately flushed with oceanic water (Bidwell Headwaters, Cedar Swamp Creek, Dennis Creek) or are poorly flushed (Cedar Headwaters, Dias Headwaters, Sunray, Two Mile Beach Unit). Most of the marsh management units are relatively unaltered by areas of fill such as dikes, roads, or dredge spoil deposits, but there is moderate fill and habitat fragmentation within the Cedar Swamp Creek, Sunray, and Mud Creek marsh management units, and this type of disturbance is severe within Two Mile Beach Unit and Baldridge marsh management units.

Historic ditching is extensive within two marsh management units (Dias Creek and Reeds Beach). During 2012–16, average surface-water salinities in the summer ranged from about 6 to about 33 parts per thousand (ppt; mesohaline to euhaline as defined by Cowardin and others, 1979) within the Cape May National Wildlife Refuge marshes and was about 2 ppt (oligohaline as defined by Cowardin and others, 1979) at the Supawna Meadows National Wildlife Refuge. Invasive plants are present in all the marsh management units (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017).

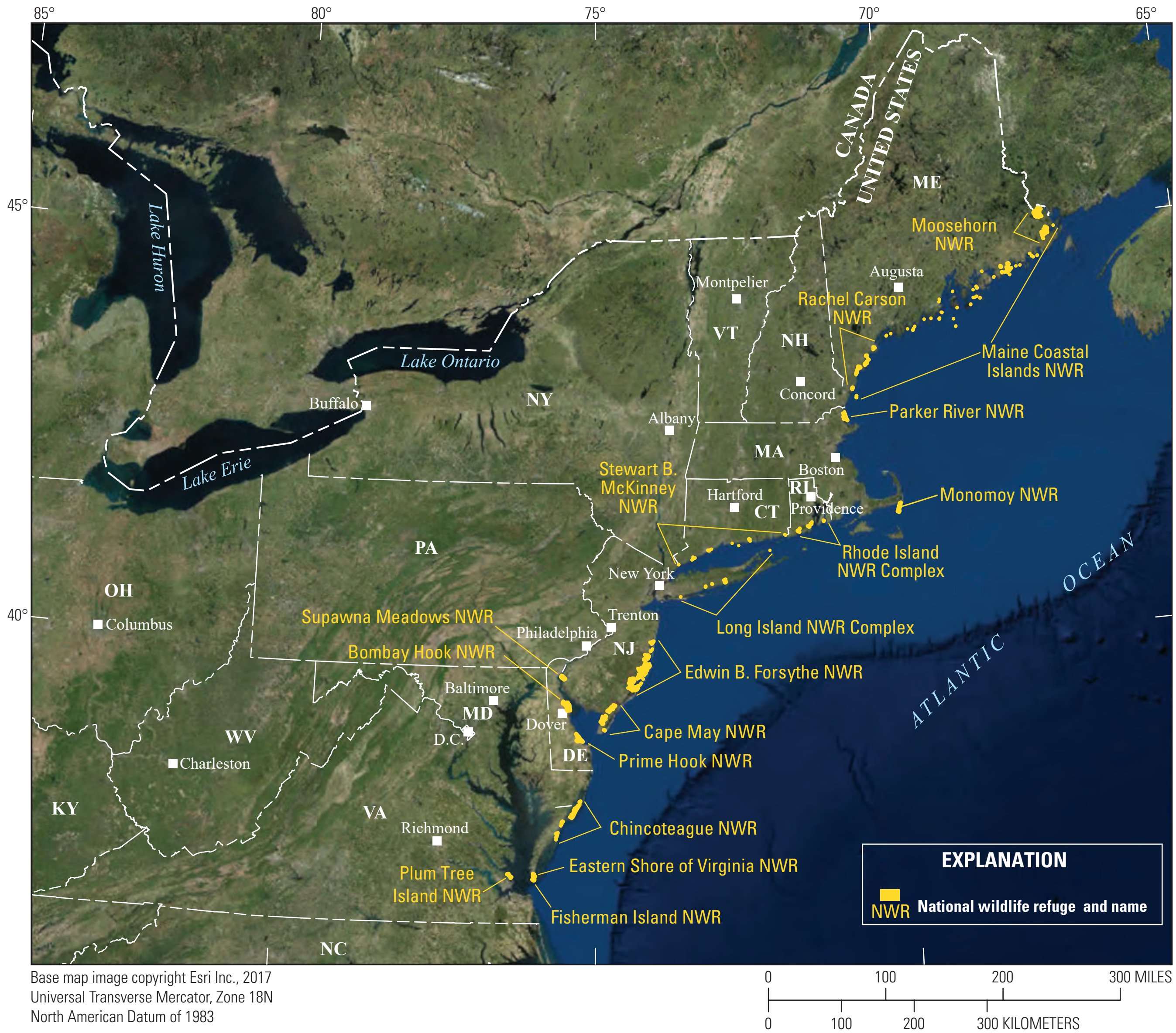

Figure 1. National wildlife refuges and national wildlife refuge complexes of the U.S. Fish and Wildlife Service where salt marsh integrity was assessed from 2012 to 2016 using the regional monitoring protocol.

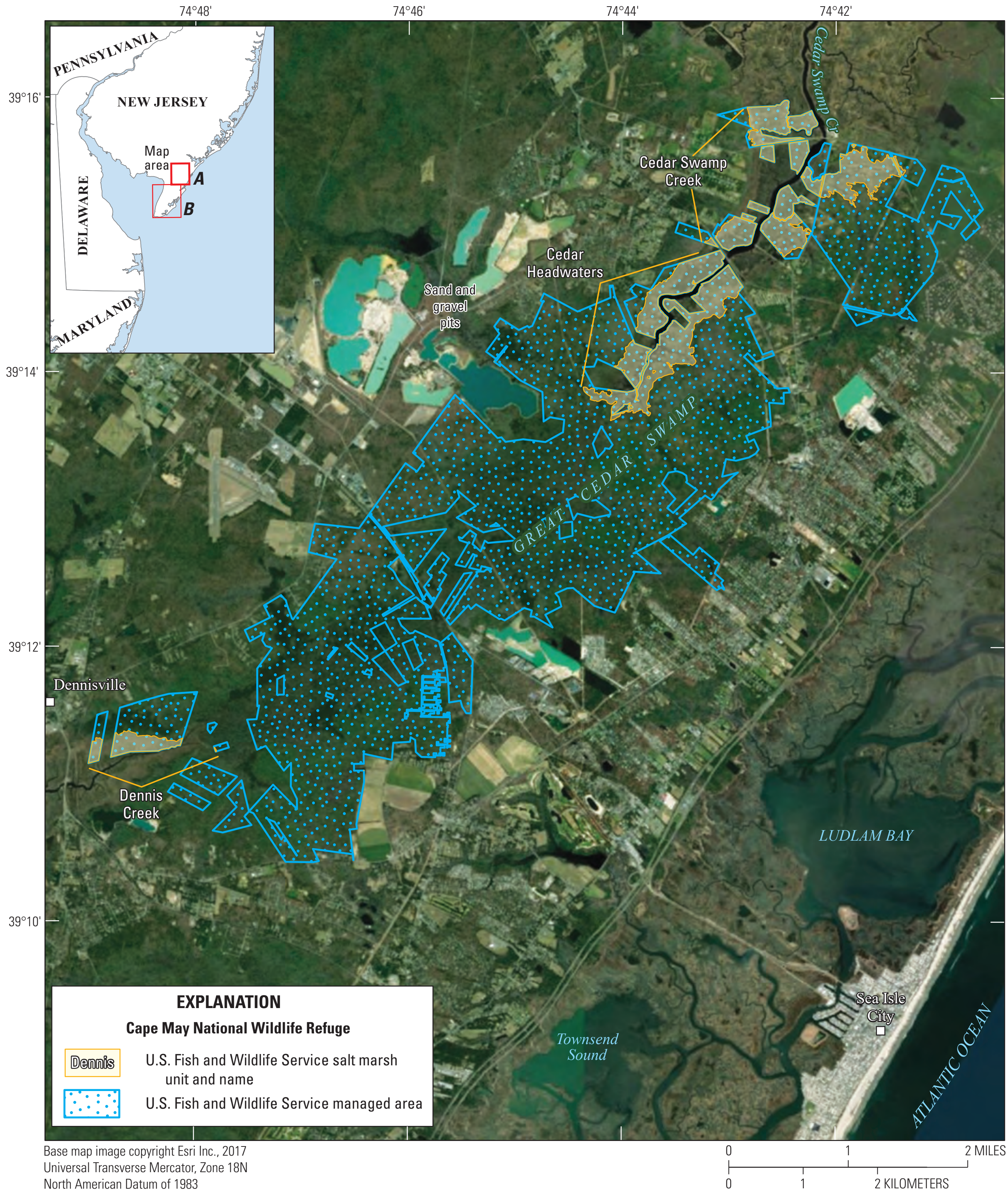

Figure 2. Marsh management units at the *A*, northern and *B*, southern parts of the Cape May National Wildlife Refuge in New Jersey.

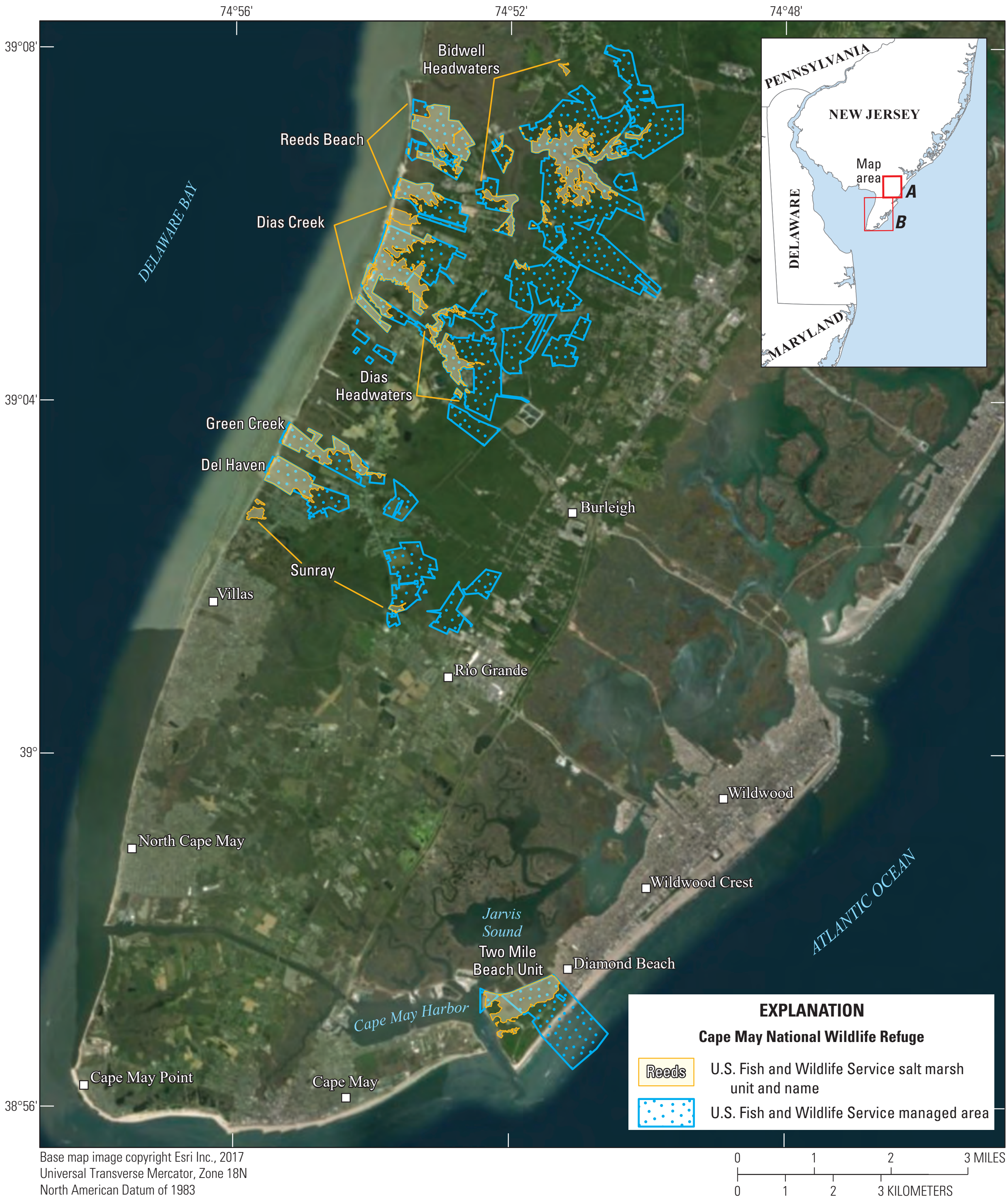

Figure 2. Marsh management units at the *A*, northern and *B*, southern parts of the Cape May National Wildlife Refuge in New Jersey.—Continued

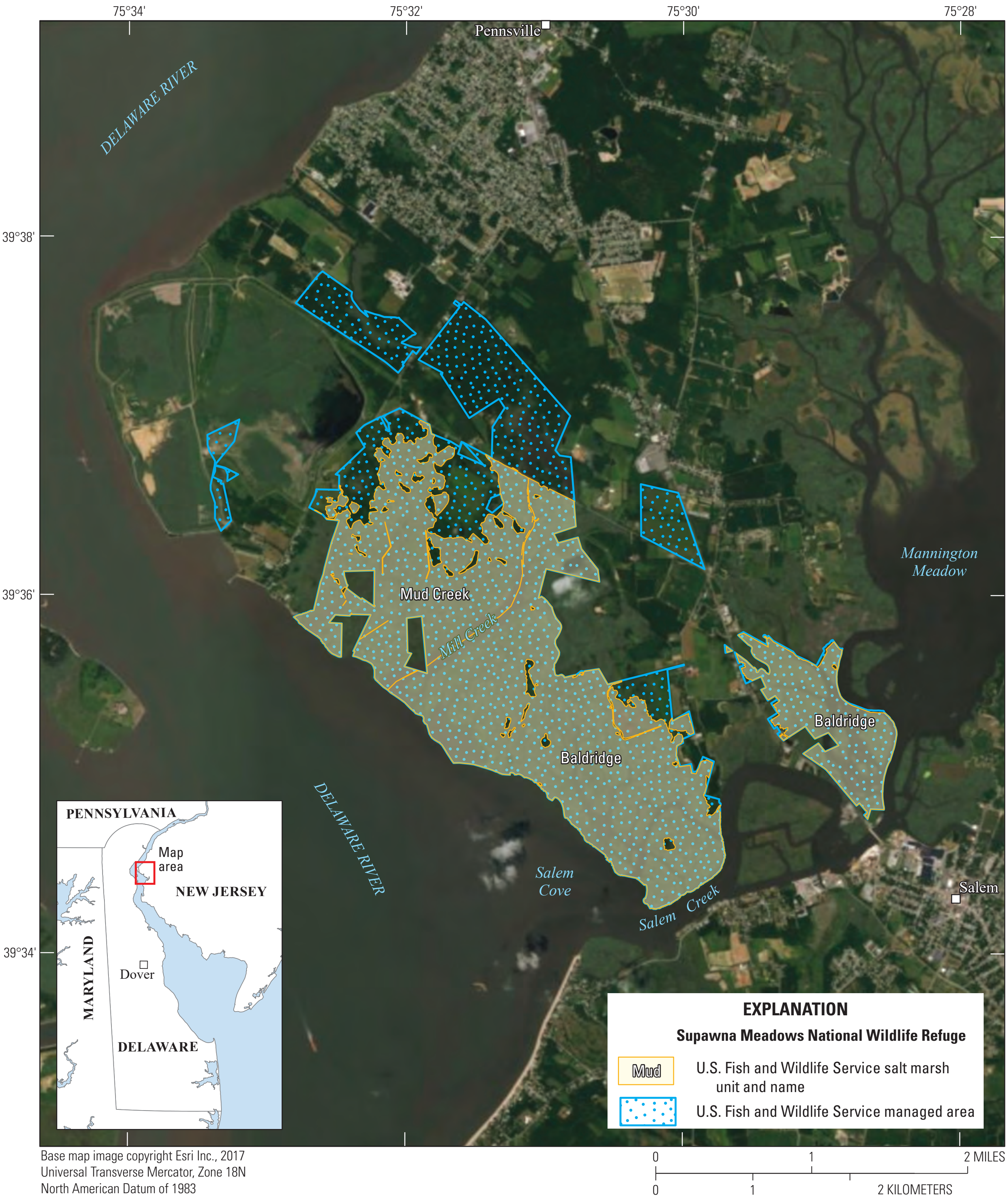

Figure 3. Marsh management units at the Supawna Meadows National Wildlife Refuge in New Jersey.

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 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 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) provided details regarding development of the structured decision-making framework and a case-study application to Prime Hook National Wildlife Refuge.

Application to the Cape May and Supawna Meadows National Wildlife Refuges

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 Cape May and Supawna Meadows National Wildlife Refuges and estimated the total cost of implementation over 5 years. Potential actions to enhance salt marsh

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 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 one. The weight for each metric is the product of the weights from each level of the hierarchy leading to that metric. NA, not applicable; See also Neckles and others (2015)]

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 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 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.

integrity ranged from focused efforts that restore hydrologic connections, control *Phragmites*, or protect shorelines, to larger scale projects that alter marsh elevation or vegetation succession (table 3, in back of report). 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. 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, in back of report; 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, in back of report). 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

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

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 $25,000 increments up to $50,000; in $50,000 increments up to $100,000; in $100,000 increments up to $1 million; in $500,000 increments up to $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 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

Management actions identified to improve marsh integrity at the Cape May and Supawna Meadows National Wildlife Refuges included strategies to restore or enhance physical marsh features (using actions such as thin layer deposition), protect shorelines from erosion, create nesting habitat for migratory birds, manage native marsh vegetation, and reduce the spread of *Phragmites* (table 3, in back of report). For costs ranging from $0 to $11.3 million, the estimated management benefits for individual actions across all metrics, measured as weighted utilities, ranged from 0.389 (for controlling *Phragmites* with herbicide in the Dias Headwaters marsh management unit of the Cape May National Wildlife Refuge) to 0.929 (for improving hydrology in the Two Mile Beach Unit of the Cape May National Wildlife Refuge), out of a maximum possible total management benefit of 1.0 (tables 3 and 4, in back of report). In each marsh management unit, the option with both the lowest management benefit and lowest cost was generally the “no action” alternative. However, in Two Mile Beach Unit, the action to acquire the remaining U.S. Coast Guard property also had no associated cost. In addition, in many marsh management units, implementing *Phragmites* control with herbicide, in the absence of any other management action, 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 refuges. As total cost increased from $0 (no action in most units) to approximately $43 million, the total management benefit at the refuge scale increased by 67 percent, from 6.535 to 10.932 (table 5) out of a possible maximum of 13.0 (the maximum possible management benefit of 1.0 for any management action, summed across 13 marsh management units). Graphical analysis showed a consistent increase in management benefit as costs increased to $785,000 (fig. 4, portfolio 11). As expenditures increased beyond the cost of portfolio 11, 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 $10 million (fig. 4, portfolio 17).

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 11). At the Cape May National Wildlife Refuge, where thin layer deposition was identified as a potential management action (Bidwell Headwaters, Cedar Swamp Creek, Cedar Swamp

Table 5. Actions included in various management portfolios to maximize the total management benefits subject to increasing cost constraints at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.

[Letter designations for actions refer to specific actions and are listed in tables 3 and 4. Portfolios represent the combination of 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 total cost represents the sum of costs estimated for each action included in the portfolio. The maximum possible total management benefit for the refuge is 13, derived as the maximum possible total management benefit of 1.0 for any management action within one management unit, summed across 13 units. NWR, National Wildlife Refuge; NA, no action]

Portfolio	Marsh management unit													Total cost (dollars)	Total management benefit
	Cape May NWR											Supawna Meadows NWR			
	Bidwell Headwaters	Cedar Swamp Creek	Cedar Swamp Headwaters	Del Haven	Dennis Creek	Dias Creek	Dias Headwaters	Green Creek	Reeds Beach	Sunray	Two Mile Beach Unit	Baldridge Creek	Mud Creek		
1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	D	NA	NA	0	6.535
2	NA	NA	NA	NA	G	NA	F	C	NA	NA	D	NA	NA	24,000	7.074
3	D	NA	NA	C	G	NA	NA	C	NA	NA	D	NA	NA	42,900	7.498
4	E	NA	NA	C	G	NA	F	C	NA	NA	D	NA	NA	98,870	7.914
5	E	D	NA	C	G	NA	F	C	NA	NA	D	NA	NA	149,620	8.265
6	E	B	NA	C	G	NA	B	C	B	NA	D	NA	NA	193,690	8.612
7	E	D	G	C	G	NA	B	C	B	NA	D	NA	NA	295,335	9.238
8	E	D	G	C	G	B	B	C	B	NA	D	NA	NA	370,335	9.505
9	E	D	G	C	G	B	B	C	B	NA	D	B	NA	466,335	9.522
10	E	D	G	C	G	B	B	C	B	E	D	NA	NA	688,635	9.756
11	E	D	G	C	G	B	B	C	B	E	D	B	NA	784,635	9.772
12	E	D	G	C	G	B	B	C	F	E	D	B	NA	951,635	9.773
13	E	D	G	C	G	B	B	C	F	E	D	B	B	1,476,635	10.001
14	E	D	G	C	G	B	B	C	B	D	D	B	B	1,891,335	10.080
15	E	D	G	C	G	D	B	C	F	D	D	B	B	2,208,335	10.081
16	E	D	G	C	G	D	B	C	F	D	D	E	B	4,912,335	10.377
17	E	D	G	C	G	D	B	C	F	D	C	A	D	9,904,335	10.673
18	E	H	G	C	I	D	A	C	F	D	B	E	D	14,958,435	10.816
19	E	H	G	C	I	D	A	H	F	C	G	D	D	24,508,435	10.897
20	E	H	I	C	I	B	A	C	B	C	G	D	D	29,909,935	10.927
21	E	H	I	C	I	D	A	H	F	C	G	F	D	31,972,935	10.930
22	E	H	I	C	I	D	A	H	G	C	G	F	D	38,305,935	10.930
23	E	H	I	C	I	D	A	H	H	C	G	D	D	42,967,015	10.932

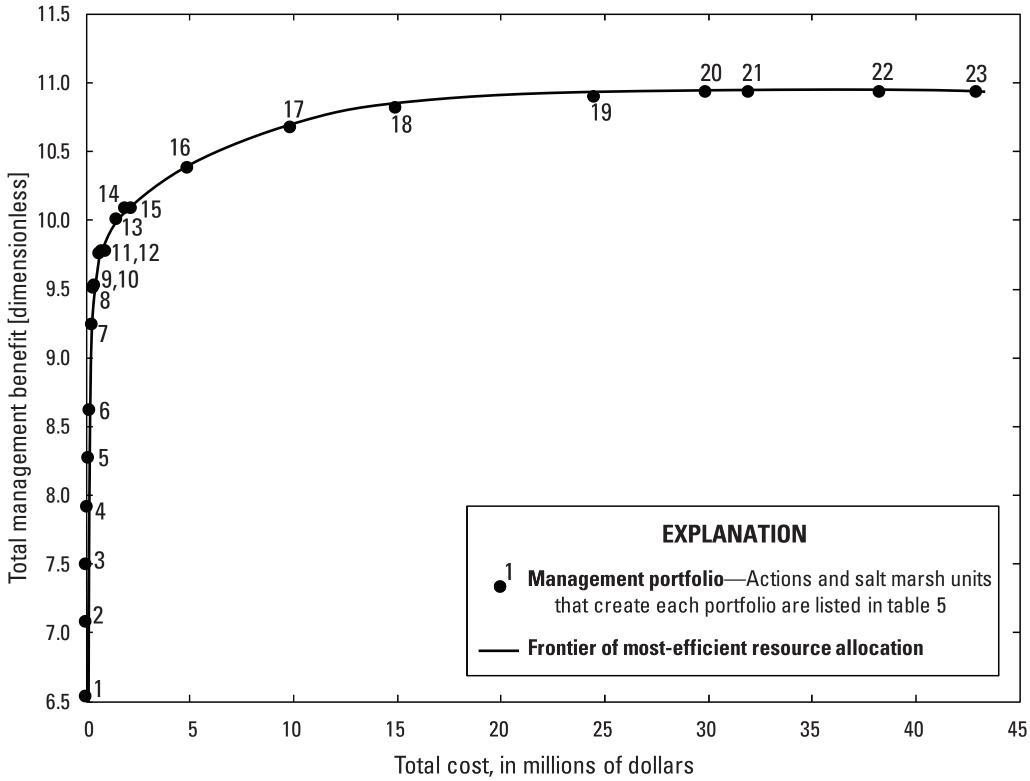

Figure 4. Predicted total management benefit of various portfolios, expressed as weighted utilities, relative to total annual cost at the Cape May and Supawna Meadows National Wildlife Refuges in New Jersey. Each portfolio (dot with number) represents a combination of thirteen management actions, one per marsh management unit, as identified in table 5. The line represents the efficient frontier for resource allocation.

Headwaters, Del Haven, Dennis Creek, Green Creek, and Reeds Beach management units) it was nearly always included in the optimal portfolios. At Two Mile Beach Unit, the no-cost action to acquire the remaining U.S. Coast Guard property (action D) was consistently selected. For other marsh management units, actions related to hydrologic remediation (Dias Creek and Dias Headwaters) or managing invasive vegetation (Sunray) were selected. At the Supawna Meadows National Wildlife Refuge, taking no action was generally preferable to the expenditures for performing management actions. In contrast, some management actions were never or rarely included in an optimal portfolio at either refuge. For example, although creating islands for tidal marsh obligate birds was identified to improve habitat quality at four management units (Cedar Swamp Headwaters, Cedar Swamp Creek, Dennis Creek, and Two Mile Beach Unit), this action was never selected due to the high cost ($374,000 to $1,123,000 per management unit) relative to the total management benefit accrued. Similarly, the optimal portfolios never included installation of offshore protection or living shorelines (shorelines that use plants or other natural elements to stabilize estuarine coasts, bays, or tributaries), which were identified as possible actions within the Cedar Swamp Headwaters, Cedar Swamp Creek, Del Haven, Dennis Creek, Green Creek, Baldridge Creek, and Mud Creek management units. Finally, although *Phragmites* control was included in the potential management actions for 11 management units (all except Dias Creek and Reeds Beach), it was selected for only 4 units (Cedar Swamp Creek, Cedar Swamp Headwaters, Sunray, and Baldridge Creek).

Examination of the refuge-scale metric responses to actions included in portfolio 11, which is the turning point in the cost-benefit plot (fig. 4), revealed how implementation would affect specific management objectives. The actions included in portfolio 11 generated a prediction of modest gains in the overall management benefits derived from changes to the numbers of tidal marsh obligate birds and to flooding duration, and large gains in the density of spiders (as an indicator of trophic health) and the capacity of marsh elevation to keep pace with sea-level rise (fig. 5). Ecologically, the combination of actions in this portfolio may result in an average 112-percent increase in tidal marsh obligate bird counts (averaged across all units), 1,553-percent increase in spider density, 12-percent increase in native vegetation cover, and 48-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 7 and the “no-action” alternative; table 3, in back of report). Implementation of actions in this portfolio was predicted to increase the capacity for marsh elevation to keep pace with sea-level rise in 10 of the 13 marsh management units. The management benefits predicted for portfolios 1 through 8, at total costs up to about half that of portfolio 11, were derived primarily from expected improvements in the capacity for marsh elevation to keep pace with sea-level rise and from presumed increases in spider density (tables 3 and 4, in back of report).

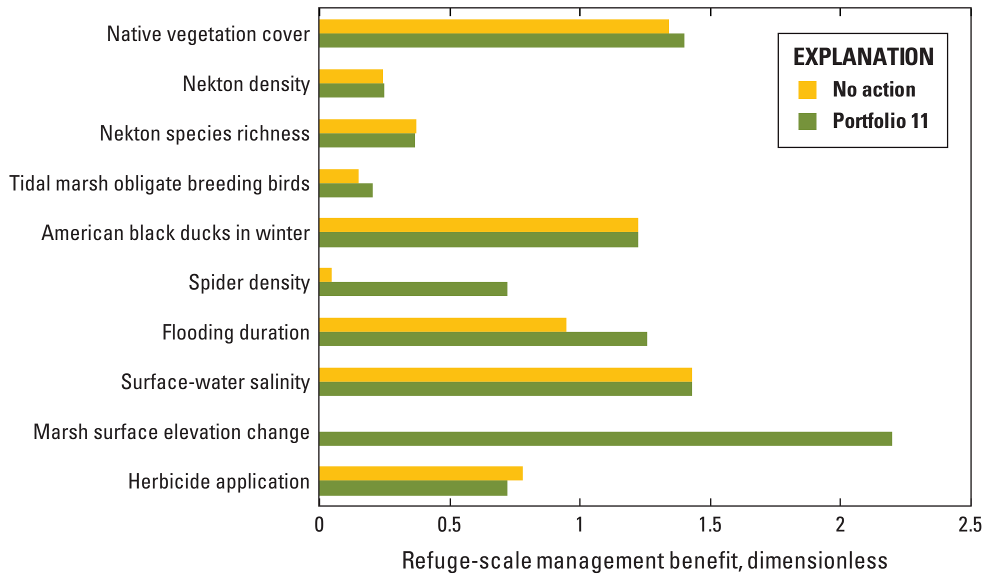

Figure 5. Predicted management benefit at the refuge scale for individual performance metrics, expressed as weighted utilities, resulting from implementation of the management actions included in portfolio 11, in comparison to the management benefit from the baseline "no-action" portfolio, at the Cape May and Supawna Meadows National Wildlife Refuges in New Jersey. Baseline ("no-action") predicted management benefit for marsh surface elevation change is zero. 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 Cape May and Supawna Meadows National Wildlife Refuges. 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, in back of report) were based on current understanding of the Cape May and Supawna Meadows 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). Thin-layer deposition of dredged sediments on the marsh surface is increasingly proposed to enhance sustainability of northeastern salt marshes threatened with submergence (Wigand and others, 2017). In this prototype, the relatively low cost-estimate and high management benefit associated with thin-layer deposition led to its frequent selection within optimal portfolios. Multiple, interacting factors influence the long-term success of sediment additions in prolonging marsh integrity, and coastal managers are evaluating its efficacy as a management strategy for improving marsh resilience (Roman, 2017). Future iterations of this decision model can incorporate improved understanding of implementation costs for thin-layer deposition and marsh response.

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 very coarse scale of measurement for change in marsh surface elevation relative to sea-level rise (table 1). In 2013, surface elevation tables (Lynch and others, 2015) were installed in each marsh management unit 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 refuge decision making. First, construction of islands as nesting habitat for tidal marsh obligate birds was rarely selected for implementation, suggesting that other methods focused directly on improving nest success might warrant investigation. Recent studies identify controlling predators within existing marshes (Roberts and others, 2017) and acquisition of adjacent parcels for marsh migration (Wiest and others, 2014) as approaches for limiting declines of saltmarsh sparrow populations. Second, although erosion of marsh edges is identified as a primary threat by refuge managers, reducing wave action through living shorelines or other structures was usually included within only the costliest portfolios, beyond the point of diminishing returns on investment (portfolios greater than or equal to the cost of portfolio 17; fig. 4; table 5). This might lead managers to reconsider living shoreline as a management option at these refuges. Alternatively, 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 shoreline erosion. Third, the transparency of the structured decision-making framework reveals the tradeoffs associated with herbicide application for controlling *Phragmites*. Spread of *Phragmites* is a management concern at the Cape May and Supawna Meadows National Wildlife Refuges, and this prototype could be adapted to allow managers to evaluate the relative expected benefits and detriments of chemical and other control methods (table 3, in back of report). These results emphasize the importance that refuge managers have already placed on controlling spread of *Phragmites* through various methods, including mowing and prescribed burning, that minimize environmental risks (FWS, 2004, 2011). Finally, the constrained optimizations analyzed in this report 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 Cape May and Supawna Meadows National Wildlife Refuges 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 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 Cape May and Supawna Meadows National Wildlife Refuges 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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Tables 3–4

Table 3. Possible management actions for achieving objectives within marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.

[Potential management actions, costs, and predicted outcomes were developed by workshop participants using expert judgement. Predicted consequences of management actions were aided by influence diagrams (app. 1). ppt, part per thousand; ac, acre; ft, foot; %, percent]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton		Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Hydrology		Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
			Density (number of animals per square meter)	Species richness (number)				Duration of surface flooding[2] (%)	Surface-water salinity[2] (ppt)		
Cape May											
Bidwell Headwaters											
No action	0	85	12.78	8	4.23	High	1	46.53	0	0	0
A. Improving tidal flow (expand bridge to widen waterway underneath)	3,500,000	90	13	7	5	High	15	40	0	0	0
B. Phragmites control to increase transition zone	34,000	95	12.78	8	4.77	High	1	46.53	0	0	1
C. Native plant replacement (with Phragmites control)	3,034,000	97	12.78	8	5	High	1	46.53	0	0	1
D. Contaminants education (for marina)	500	85	12.78	8	4.23	High	1	46.53	0	0	0
E. Thin layer deposition (386 acres)	55,970	85	12.78	7	5.58	High	30	5	3	1	0
F. Small channel excavation	177,500	90	20	7	5	High	15	15	1	1	0
G. B+E	89,970	90	20	7	6	High	30	15	1	1	1
Cedar Swamp Creek											
No action	0	61	8.81	4	7.98	Medium	1	5.03	0	0	0
A. Islands for tidal marsh obligate birds	374,344	61	9.25	4	10	High	1	5.03	0	0	0
B. Phragmites control	19,000	92	8.81	4	11.09	Medium	15	5.03	0	0	0
C. Living shoreline (coir logs along interior of creek, 4,200 ft)	1,575,000	61	8.81	4	8.78	High	1	5.03	0	0	0
D. Thin layer deposition to achieve 40% inundation (350 acres)	50,750	95	10	4	22	Medium	30	0	0	1	0
E. A+C	1,949,344	90	10	4	12	High	1	0	0	0	0
F. A+B	393,344	90	10	4	11	High	15	0	0	1	1
G. B+C	1,594,000	90	10	4	12	High	15	0	0	1	1
H. C+D	1,625,750	95	10	4	26	Medium	30	0	0	1	0
I. Remove Upper Bridge Road	156,600	65	8.81	4	10	Medium	15	5	0	0	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[Potential management actions, costs, and predicted outcomes were developed by workshop participants using expert judgement. Predicted consequences of management actions were aided by influence diagrams (app. 1). ppt, part per thousand; ac, acre; ft, foot; %, percent]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton		Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Hydrology		Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
			Density (number of animals per square meter)	Species richness (number)				Duration of surface flooding[2] (%)	Surface-water salinity[2] (ppt)		
Cedar Swamp Headwaters											
No action	0	76	5.63	3	0	Medium	1	16.68	0	0	0
A. Improving tidal flow (expand bridge to widen waterway underneath)	3,500,000	76	5.63	4	0	Medium	1	14	0	0	0
B. Islands for tidal marsh obligate birds	374,344	76	5.9	4	2	High	1	16.68	0	0	0
C. Phragmites control	19,000	85	5.63	3	0	Medium	15	16.68	0	0	1
D. Thin layer deposition to achieve 40% inundation or less (351 acres)	50,895	76	5.9	3	4	Medium	30	0	1	1	0
E. B+C	393,344	80	6	4	6	High	15	16.68	1	1	0
F. B+D	425,239	84	8	4	6	High	30	0	1	0	0
G. C+D	69,895	82	6	3	4	Medium	30	0	1	1	0
H. Living shoreline (19,700 ft)	7,387,500	80	6	4	2	High	1	10	1	1	0
I. D+H	7,438,395	80	7	4	6	High	30	0	1	1	0
Del Haven											
No action	0	91	60.26	7	6.72	High	1	49.06	0	0	0
A. Phragmites control (18 acres)	3,500	92	60.26	7	7	High	1	49.06	0	0	1
B. Native planting to create transition zone and change in elevation, with Phragmites control	500,000	95	60.26	7	8	High	1	49.06	0	0	0
C. Thin layer deposition (128 acres)	18,900	91	58	7	10	High	30	10	0	1	0
D. Increase sinuosity of creeks (5,700 ft)	243,000	91	61	7	7	High	15	16	0	1	0
E. Grid-ditch remediation (fill, increase sinuosity, and so on, 5,700 ft)	250,000	91	59	7	7	High	1	30	0	1	0
G. Remove wing walls	350,000	91	65	7	7	High	1	40	0	0	0
H. Living shoreline (1,900 ft)	712,500	91	70	7	8	High	15	10	0	1	0
I. Rock/rip-rap to slow water flow, wave attenuation, and so on (1,900 ft)	815,100	91	72	7	7	High	15	10	0	1	0
J. B+E	750,000	92	62	7	9	High	1	20	0	1	0
K. B+C	518,900	95	58	7	10	High	30	25	0	1	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[Potential management actions, costs, and predicted outcomes were developed by workshop participants using expert judgement. Predicted consequences of management actions were aided by influence diagrams (app. 1). ppt, part per thousand; ac, acre; ft, foot; %, percent]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton		Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Hydrology		Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
			Density (number of animals per square meter)	Species richness (number)				Duration of surface flooding[2] (%)	Surface-water salinity[2] (ppt)		
Dennis Creek											
No action	0	75	87.28	3	1.62	Medium	15	0.63	1	0	0
A. Improve tidal flow under two bridges (to widen waterway underneath)	1,100,000	75	90	3	2	Medium	15	3	0	0	0
B. Islands for tidal marsh obligate birds	374,344	75	88	3	2.6	High	15	0.63	1	0	0
C. Phragmites control (9 acres)	2,500	85	87.28	3	2	Medium	15	0.63	1	0	1
D. Living shoreline (coir logs along interior of creek, 3,700 ft)	1,387,500	75	88	3	1.8	High	15	0.63	1	1	0
E. Forced marsh migration (remove dead trees, girdling some others, 9 acres)	150,000	75	87.28	3	1.62	High	15	0.63	1	0	0
F. C+E	152,500	85	87.28	3	2.04	High	15	0.63	1	0	1
G. Thin layer deposition (50 acres)	8,500	75	100	3	5	Medium	30	6	0	1	0
H. D+F	1,540,000	80	100	3	3	High	15	0	0	1	0
I. D+G	1,396,000	75	110	3	6	High	30	3	0	1	0
Dias Creek											
No action	0	98	51.45	5	8.91	High	1	0.55	0	0	0
A. Contaminants education	500	98	51	5	9	High	1	0.55	0	0	0
B. Grid-ditch remediation (fill ditches, 23,000 ft)	75,000	98	53	5	10	High	15	0.55	0	1	0
C. Increase sinuosity of large, L-shape channel (4,800 ft)	150,000	98	52	5	9	High	15	0.55	0	1	0
D. B+C	225,000	98	54	5	10	High	15	0.55	0	1	0
Dias Headwaters											
No action	0	75	16.73	5	15.96	High	1	74	0	0	0
A. Improve tidal flow under bridge to widen waterway underneath	1,100,000	75	18	5	16	High	15	24	0	1	0
B. Small channel excavation (2,000 ft)	33,400	75	18	5	16	High	15	34	0	1	0
C. Fill in pools (15.5 acres)	600,000	83	15.057	5	17.52	High	15	39	0	1	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[Potential management actions, costs, and predicted outcomes were developed by workshop participants using expert judgement. Predicted consequences of management actions were aided by influence diagrams (app. 1). ppt, part per thousand; ac, acre; ft, foot; %, percent]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton		Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Hydrology		Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
			Density (number of animals per square meter)	Species richness (number)				Duration of surface flooding[2] (%)	Surface-water salinity[2] (ppt)		
Dias Headwaters—Continued											
D. Phragmites control (30 acres)	5,500	80	16.73	5	19.92	High	1	74	0	0	1
E. Native plant replacement, with Phragmites control	300,000	85	16.73	5	20	High	1	74	0	0	0
F. Contaminants education	500	75	16.73	5	15.96	High	1	74	0	0	0
G. C+E	900,000	82	18	5	18	High	15	39	0	1	0
Green Creek											
No action	0	95	56.59	8	1.68	High	1	1.73	0	0	0
A. Phragmites control (55 acres)	8,500	95	56.59	8	2	High	15	1.73	0	0	1
B. Living shoreline (4,400 ft)	1,650,000	95	65	8	4	High	1	1	0	1	0
C. Thin layer deposition (70 acres)	15,000	95	54	8	4	High	15	1	0	1	0
D. Increase sinuosity of creeks (4,400 ft)	2,860,000	95	57	8	5	High	1	0	0	1	0
F. Improve tidal flow (culvert)	1,750,000	95	59	8	2	High	1	2	0	1	0
G. Rock/rip-rap to slow water flow, wave attenuation, and so on (2,200 ft)	943,800	95	60	8	2	High	1	0	0	1	0
H. B+C	1,665,000	95	60	8	4	High	15	0	0	1	0
I. D+G	3,803,800	95	60	8	3	High	1	0	0	1	0
Reeds Beach											
No action	0	99	34.06	6	5.04	High	1	17.82	7	0	0
A. Small channel excavation (10,000 ft, additional to restoration project)	167,000	99	36	6	6	High	1	12	7	1	0
B. Thin layer deposition (296 acres)	42,920	99	35	6	7	High	30	10	7	1	0
C. Increase sinuosity of creeks (7,500 ft)	4,800,000	99	35	6	6	High	30	5	7	1	0
D. Grid-ditch remediation (fill, 10,000 ft)	6,500,000	99	35	6	6	High	30	5	7	1	0
E. Improve tidal flow (widen two culverts)	3,200,000	99	35	6	6	High	30	1	7	1	0
F. A+B	209,920	99	36	6	7	High	30	5	7	1	0
G. B+D	6,542,920	99	36	6	7	High	30	4	7	1	0
H. C+D	11,300,000	99	36	6	8	High	30	5	7	1	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[Potential management actions, costs, and predicted outcomes were developed by workshop participants using expert judgement. Predicted consequences of management actions were aided by influence diagrams (app. 1). ppt, part per thousand; ac, acre; ft, foot; %, percent]

Management action	Estimated cost over 5 years (dollars)	Performance metrics									
		Native vegetation (% cover)	Nekton		Tidal marsh obligate birds (summed number per point)	American black ducks use[1]	Spider density (number per square meter)	Hydrology		Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
			Density (number of animals per square meter)	Species richness (number)				Duration of surface flooding[2] (%)	Surface-water salinity[2] (ppt)		
Sunray											
No action	0	62	0.67	3	0	High	1	22.27	0	0	0
A. Native plant replacement (10 acres)	315,000	80	2	3	2	High	1	22.27	0	0	0
B. Phragmites Control (15 acres)	3,300	70	0.67	3	2	High	1	22.27	0	0	1
C. Open tidal flow to beach (breach dunes in two places)	1,700,000	65	6	5	3	High	15	5	10	1	0
D. Improve tidal flow through culvert and woods (300 ft and culvert under road)	900,000	65	6	5	2	High	15	5	10	1	0
E. A+B	318,300	85	3	3	4	High	1	20	0	1	0
F. A+C	2,015,000	85	6	3	4	High	15	20	0	1	0
Two Mile Beach Unit											
No action	0	98	77.13	6	53.35	High	1	12.46	7	0	0
A. Island for tidal marsh obligate birds	1,123,031	98	80	6	60	High	1	12.46	7	0	0
B. Widen culvert, improve tidal flow	3,500,000	98	80	6	70	High	15	20	7	1	0
C. Fill pools and creeks for plant colonization (66 acres)	3,400,000	98	80	6	70	High	15	20	7	1	0
D. Acquire remainder of U.S Coast Guard property (500 acres)	0	98	77.13	6	55	High	1	12.46	7	0	0
E. Remove tower to decrease bird mortality on guy wires	3,500,000	98	77.13	6	60	High	1	12.46	7	0	0
F. Phragmites control (3 acres)	1,000	98	77.13	6	58	High	1	12.46	7	0	1
G. B+C	6,900,000	98	82	6	72	High	15	12.46	7	1	0
H. D+E	3,500,000	99	77.13	6	62	High	1	12.46	7	0	0

Table 3. Possible management actions for achieving objectives within marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[Potential management actions, costs, and predicted outcomes were developed by workshop participants using expert judgement. Predicted consequences of management actions were aided by influence diagrams (app. 1). ppt, part per thousand; ac, acre; ft, foot; %, percent]

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)	Hydrology: Duration of surface flooding[2] (%)	Hydrology: Surface-water salinity[2] (ppt)	Marsh surface elevation change relative to sea-level rise[3]	Herbicide application[4]
Supawna Meadows											
Baldridge Creek											
No action	0	29.5	1.25	4	1	High	1	22.15	0	0	0
A. Living shoreline (5,000 ft, just around the northern side of Salem River)	1,875,000	30	3	4	2	High	1	18	0	1	0
B. Phragmites control (1,600 acres)	96,000	45	1.25	4	3	High	15	20	0	0	1
C. Breakwater remediation (including Goose Pond, Baldridge Creek, and North bank of Salem River near Hickory Island)	3,150,000	30	1.25	4	2	High	1	15	0	1	0
D. Marsh platform gradation (1,600 acres)	6,500,000	30	3	4	2	High	30	0	0	1	0
E. Improve tidal flow under bridge (improve scour areas on the East side of bridge over Salem River)	2,800,000	30	3	4	1	High	15	5	0	1	0
F. B+D	6,596,000	30	3	4	2	High	30	5	0	1	0
G. Fill in Goose Pond (40 acres)	6,000,000	32	4	4	3	High	1	10	0	1	0
Mud Creek											
No action	0	24.5	8.8	4	1	High	1	5.22	0	0	0
A. Phragmites control (700 acres)	42,000	26	8.8	4	3	High	15	4	0	0	1
B. Breakwater remediation (1,050 ft Mud Creek mouths)	525,000	28	10	4	2	High	1	4	0	1	0
C. Marsh platform gradation (700 acres)	3,000,000	25	10	4	2	High	30	5	0	1	0
D. A+C	3,042,000	40	11	4	4	High	30	2	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, lower than sea-level rise; 1, above sea-level rise; 0.5, intermediate.

[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 13 marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, 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. CM, Cape May; SM, Supawna Meadows. ac, acre; ft, foot]

Management action	Performance metrics										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			
CM-Bidwell Headwaters											
No action	0.113	0.010	0.045	0.006	0.1	0	0	0.11	0	0.06	0.444
A. Improving tidal flow (expand bridge to widen waterway underneath)	0.116	0.010	0.039	0.007	0.1	0.045	0	0.11	0	0.06	0.487
B. Phragmites control to increase transition zone	0.118	0.010	0.045	0.007	0.1	0	0	0.11	0	0	0.390
C. Native plant replacement (with Phragmites control)	0.119	0.010	0.045	0.007	0.1	0	0	0.11	0	0	0.391
D. Contaminants education (for marina)	0.113	0.010	0.045	0.006	0.1	0	0	0.11	0	0.06	0.444
E. Thin layer deposition (386 acres)	0.113	0.010	0.039	0.008	0.1	0.09	0.11	0.11	0.22	0.06	0.861
F. Small channel excavation	0.116	0.015	0.039	0.007	0.1	0.045	0.092	0.11	0.22	0.06	0.804
G. B+E	0.116	0.015	0.039	0.008	0.1	0.09	0.092	0.11	0.22	0	0.790
CM-Cedar Swamp Creek											
No action	0.098	0.007	0.023	0.011	0.075	0	0.11	0.11	0	0.06	0.494
A. Islands for tidal marsh obligate birds	0.098	0.007	0.023	0.014	0.1	0	0.11	0.11	0	0.06	0.522
B. Phragmites control	0.117	0.007	0.023	0.015	0.075	0.045	0.11	0.11	0	0.06	0.562
C. Living shoreline (coir logs along interior of creek, 4,200 ft)	0.098	0.007	0.023	0.012	0.1	0	0.11	0.11	0	0.06	0.520
D. Thin layer deposition to achieve 40% inundation (350 acres)	0.118	0.008	0.023	0.031	0.075	0.09	0.11	0.11	0.22	0.06	0.844
E. A+C	0.116	0.008	0.023	0.017	0.1	0	0.11	0.11	0	0.06	0.543
F. A+B	0.116	0.008	0.023	0.015	0.1	0.045	0.11	0.11	0.22	0	0.747
G. B+C	0.116	0.008	0.023	0.017	0.1	0.045	0.11	0.11	0.22	0	0.748
H. C+D	0.118	0.008	0.023	0.036	0.075	0.09	0.11	0.11	0.22	0.06	0.850
I. Remove Upper Bridge Road	0.101	0.007	0.023	0.014	0.075	0.045	0.11	0.11	0	0.06	0.544

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within 13 marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, 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. CM, Cape May; SM, Supawna Meadows. ac, acre; ft, foot]

Management action	Performance metrics										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			
CM-Cedar Swamp Headwaters											
No action	0.108	0.005	0.017	0.000	0.075	0	0.086	0.11	0	0.06	0.460
A. Improving tidal flow (expand bridge to widen waterway underneath)	0.108	0.005	0.023	0.000	0.075	0	0.095	0.11	0	0.06	0.476
B. Islands for tidal marsh obligate birds	0.108	0.005	0.023	0.003	0.1	0	0.086	0.11	0	0.06	0.494
C. Phragmites control	0.113	0.005	0.017	0.000	0.075	0.045	0.086	0.11	0	0	0.450
D. Thin layer deposition to achieve 40% inundation or less (351 acres)	0.108	0.005	0.017	0.006	0.075	0.09	0.11	0.11	0.22	0.06	0.801
E. B+C	0.111	0.005	0.023	0.008	0.1	0.045	0.086	0.11	0.22	0.06	0.767
F. B+D	0.113	0.007	0.023	0.008	0.1	0.09	0.11	0.11	0	0.06	0.620
G. C+D	0.112	0.005	0.017	0.006	0.075	0.09	0.11	0.11	0.22	0.06	0.804
H. Living shoreline (19,700 ft)	0.111	0.005	0.023	0.003	0.1	0	0.11	0.11	0.22	0.06	0.741
I. D+H	0.111	0.006	0.023	0.008	0.1	0.09	0.11	0.11	0.22	0.06	0.837
CM-Del Haven											
No action	0.116	0.034	0.039	0.009	0.1	0	0	0.11	0	0.06	0.469
A. Phragmites control (18 acres)	0.117	0.034	0.039	0.010	0.1	0	0	0.11	0	0	0.409
B. Native planting to create transition zone and change in elevation, with Phragmites control	0.118	0.034	0.039	0.011	0.1	0	0	0.11	0	0.06	0.472
C. Thin layer deposition (128 acres)	0.116	0.033	0.039	0.014	0.1	0.09	0.11	0.11	0.22	0.06	0.892
D. Increase sinuosity of creeks (5,700 ft)	0.116	0.034	0.039	0.010	0.1	0.045	0.088	0.11	0.22	0.06	0.822
E. Grid-ditch remediation (fill, increase sinuosity, and so on, 5,700 ft)	0.116	0.033	0.039	0.010	0.1	0	0.037	0.11	0.22	0.06	0.725
G. Remove wing walls	0.116	0.035	0.039	0.010	0.1	0	0	0.11	0	0.06	0.470
H. Living shoreline (1,900 ft)	0.116	0.037	0.039	0.011	0.1	0.045	0.11	0.11	0.22	0.06	0.848
I. Rock/rip-rap to slow water flow, wave attenuation, and so on (1,900 ft)	0.116	0.037	0.039	0.010	0.1	0.045	0.11	0.11	0.22	0.06	0.848
J. B+E	0.117	0.034	0.039	0.013	0.1	0	0.073	0.11	0.22	0.06	0.766
K. B+C	0.118	0.033	0.039	0.014	0.1	0.09	0.055	0.11	0.22	0.06	0.839

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within 13 marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, 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. CM, Cape May; SM, Supawna Meadows. ac, acre; ft, foot]

Management action	Performance metrics										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			
CM-Dennis Creek											
No action	0.108	0.041	0.017	0.002	0.075	0.045	0.11	0.11	0	0.06	0.568
A. Improve tidal flow under two bridge (to widen waterway underneath)	0.108	0.041	0.017	0.003	0.075	0.045	0.11	0.11	0	0.06	0.569
B. Islands for tidal marsh obligate birds	0.108	0.041	0.017	0.004	0.1	0.045	0.11	0.11	0	0.06	0.594
C. Phragmites control (9 acres)	0.113	0.041	0.017	0.003	0.075	0.045	0.11	0.11	0	0	0.514
D. Living shoreline (coir logs along interior of creek, 3,700 ft)	0.108	0.041	0.017	0.003	0.1	0.045	0.11	0.11	0.22	0.06	0.813
E. Forced marsh migration (remove dead trees, girdling some others, 9 acres)	0.108	0.041	0.017	0.002	0.1	0.045	0.11	0.11	0	0.06	0.593
F. C+E	0.113	0.041	0.017	0.003	0.1	0.045	0.11	0.11	0	0	0.539
G. Thin layer deposition (50 acres)	0.108	0.043	0.017	0.007	0.075	0.09	0.11	0.11	0.22	0.06	0.840
H. D+F	0.111	0.043	0.017	0.004	0.1	0.045	0.11	0.11	0.22	0.06	0.820
I. D+G	0.108	0.045	0.017	0.008	0.1	0.09	0.11	0.11	0.22	0.06	0.868
CM-Dias Creek											
No action	0.119	0.030	0.028	0.012	0.1	0	0.11	0.11	0	0.06	0.570
A. Contaminants education	0.119	0.030	0.028	0.013	0.1	0	0.11	0.11	0	0.06	0.570
B. Grid-ditch remediation (fill ditches, 23,000 ft)	0.119	0.031	0.028	0.014	0.1	0.045	0.11	0.11	0.22	0.06	0.837
C. Increase sinuosity of large, L-shape channel (4,800 ft)	0.119	0.031	0.028	0.013	0.1	0.045	0.11	0.11	0.22	0.06	0.835
D. B+C	0.119	0.031	0.028	0.014	0.1	0.045	0.11	0.11	0.22	0.06	0.838
CM-Dias Headwaters											
No action	0.108	0.013	0.028	0.022	0.1	0	0	0.11	0	0.06	0.441
A. Improve tidal flow under bridge to widen waterway underneath	0.108	0.014	0.028	0.022	0.1	0.045	0.059	0.11	0.22	0.06	0.765
B. Small channel excavation (2,000 ft)	0.108	0.014	0.028	0.022	0.1	0.045	0.022	0.11	0.22	0.06	0.729
C. Fill in pools (15.5 acres)	0.112	0.012	0.028	0.024	0.1	0.045	0.004	0.11	0.22	0.06	0.715
D. Phragmites control (30 acres)	0.111	0.013	0.028	0.028	0.1	0	0	0.11	0	0	0.389

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within 13 marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, 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. CM, Cape May; SM, Supawna Meadows. ac, acre; ft, foot]

Management action	Performance metrics										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			
CM-Dias Headwaters—Continued											
E. Native plant replacement, with Phragmites control	0.113	0.013	0.028	0.028	0.1	0	0	0.11	0	0.06	0.452
F. Contaminants education	0.108	0.013	0.028	0.022	0.1	0	0	0.11	0	0.06	0.441
G. C+E	0.112	0.014	0.028	0.025	0.1	0.045	0.004	0.11	0.22	0.06	0.717
CM-Green Creek											
No action	0.118	0.032	0.045	0.002	0.1	0	0.11	0.11	0	0.06	0.578
A. Phragmites control (55 acres)	0.118	0.032	0.045	0.003	0.1	0.045	0.11	0.11	0	0	0.563
B. Living shoreline (4,400 ft)	0.118	0.035	0.045	0.006	0.1	0	0.11	0.11	0.22	0.06	0.804
C. Thin layer deposition (70 acres)	0.118	0.031	0.045	0.006	0.1	0.045	0.11	0.11	0.22	0.06	0.845
D. Increase sinuosity of creeks (4,400 ft)	0.118	0.032	0.045	0.007	0.1	0	0.11	0.11	0.22	0.06	0.802
F. Improve tidal flow (culvert)	0.118	0.033	0.045	0.003	0.1	0	0.11	0.11	0.22	0.06	0.799
G. Rock/rip-rap to slow water flow, wave attenuation, and so on (2,200 ft)	0.118	0.033	0.045	0.003	0.1	0	0.11	0.11	0.22	0.06	0.799
H. B+C	0.118	0.033	0.045	0.006	0.1	0.045	0.11	0.11	0.22	0.06	0.847
I. D+G	0.118	0.033	0.045	0.004	0.1	0	0.11	0.11	0.22	0.06	0.801
CM-Reeds Beach											
No action	0.120	0.023	0.034	0.007	0.1	0	0.081	0.11	0	0.06	0.534
A. Small channel excavation (10,000 ft, additional to restoration project)	0.120	0.024	0.034	0.008	0.1	0	0.103	0.11	0.22	0.06	0.778
B. Thin layer deposition (296 acres)	0.120	0.023	0.034	0.010	0.1	0.09	0.11	0.11	0.22	0.06	0.876
C. Increase sinuosity of creeks (7,500 ft)	0.120	0.023	0.034	0.008	0.1	0.09	0.11	0.11	0.22	0.06	0.875
D. Grid-ditch remediation (fill, 10,000 ft)	0.120	0.023	0.034	0.008	0.1	0.09	0.11	0.11	0.22	0.06	0.875
E. Improve tidal flow (widen 2 culverts)	0.120	0.023	0.034	0.008	0.1	0.09	0.11	0.11	0.22	0.06	0.875
F. A+B	0.120	0.024	0.034	0.010	0.1	0.09	0.11	0.11	0.22	0.06	0.877
G. B+D	0.120	0.024	0.034	0.010	0.1	0.09	0.11	0.11	0.22	0.06	0.877
H. C+D	0.120	0.024	0.034	0.011	0.1	0.09	0.11	0.11	0.22	0.06	0.878

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within 13 marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, 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. CM, Cape May; SM, Supawna Meadows. ac, acre; ft, foot]

Management action	Performance metrics										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			
CM-Sunray											
No action	0.099	0.001	0.017	0.000	0.1	0	0.065	0.11	0	0.06	0.451
A. Native plant replacement (10 acres)	0.111	0.002	0.017	0.003	0.1	0	0.065	0.11	0	0.06	0.467
B. Phragmites Control (15 acres)	0.105	0.001	0.017	0.003	0.1	0	0.065	0.11	0	0	0.400
C. Open tidal flow to beach (breach dunes in 2 places)	0.101	0.005	0.028	0.004	0.1	0.045	0.11	0.11	0.22	0.06	0.783
D. Improve tidal flow through culvert and woods (300 ft and culvert under road)	0.101	0.005	0.028	0.003	0.1	0.045	0.11	0.11	0.22	0.06	0.782
E. A+B	0.113	0.003	0.017	0.006	0.1	0	0.073	0.11	0.22	0.06	0.702
F. A+C	0.113	0.005	0.017	0.006	0.1	0.045	0.073	0.11	0.22	0.06	0.749
CM-Two Mile Beach Unit											
No action	0.119	0.038	0.034	0.074	0.1	0	0.101	0.11	0	0.06	0.637
A. Island for tidal marsh obligate birds	0.119	0.039	0.034	0.083	0.1	0	0.101	0.11	0	0.06	0.646
B. Widen culvert, improve tidal flow	0.119	0.039	0.034	0.097	0.1	0.045	0.073	0.11	0.22	0.06	0.898
C. Fill pools and creeks for plant colonization (66 acres)	0.119	0.039	0.034	0.097	0.1	0.045	0.073	0.11	0.22	0.06	0.898
D. Acquire remainder of U.S. Coast Guard property (500 acres)	0.119	0.038	0.034	0.076	0.1	0	0.101	0.11	0	0.06	0.639
E. Remove tower to decrease bird mortality on guy wires	0.119	0.038	0.034	0.083	0.1	0	0.101	0.11	0	0.06	0.646
F. Phragmites control (3 acres)	0.119	0.038	0.034	0.081	0.1	0	0.101	0.11	0	0	0.583
G. B+C	0.119	0.040	0.034	0.100	0.1	0.045	0.101	0.11	0.22	0.06	0.929
H. D+E	0.120	0.038	0.034	0.086	0.1	0	0.101	0.11	0	0.06	0.649

Table 4. Normalized predicted outcomes and estimated total management benefits of possible management actions within 13 marsh management units at the Cape May and Supawna Meadows National Wildlife Refuges, 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. CM, Cape May; SM, Supawna Meadows. ac, acre; ft, foot]

Management action	Performance metrics										Total manage-ment benefit
	Native vegeta-tion	Nekton		Tidal marsh obligate birds	American black ducks	Spider density	Hydrology		Marsh surface elevation change	Herbicide applica-tion	
		Density	Species richness				Duration of surface flooding	Surface-water salinity			
SM-Baldridge Creek											
No action	0.062	0.001	0.023	0.001	0.1	0	0.065	0.11	0	0.06	0.422
A. Living shoreline (5000 ft, just around the north side of Salem River)	0.063	0.003	0.023	0.003	0.1	0	0.081	0.11	0.22	0.06	0.661
B. Phragmites control (1,600 acres)	0.082	0.001	0.023	0.004	0.1	0.045	0.073	0.11	0	0	0.438
C. Breakwater remediation (including Goose Pond, Baldridge Creek, and North bank of Salem River near Hickory Island)	0.063	0.001	0.023	0.003	0.1	0	0.092	0.11	0.22	0.06	0.671
D. Marsh platform gradation (1,600 acres)	0.063	0.003	0.023	0.003	0.1	0.09	0.11	0.11	0.22	0.06	0.780
E. Improve tidal flow under bridge (improve scour areas on the East side of bridge over Salem River)	0.063	0.003	0.023	0.001	0.1	0.045	0.11	0.11	0.22	0.06	0.734
F. B+D	0.063	0.003	0.023	0.003	0.1	0.09	0.11	0.11	0.22	0.06	0.780
G. Fill in Goose Pond (40 acres)	0.066	0.003	0.023	0.004	0.1	0	0.11	0.11	0.22	0.06	0.696
SM-Mud Creek											
No action	0.054	0.007	0.023	0.001	0.1	0	0.11	0.11	0	0.06	0.465
A. Phragmites control (700 acres)	0.056	0.007	0.023	0.004	0.1	0.045	0.11	0.11	0	0	0.455
B. Breakwater remediation (1,050 ft Mud Creek mouths)	0.060	0.008	0.023	0.003	0.1	0	0.11	0.11	0.22	0.06	0.693
C. Marsh platform gradation (700 acres)	0.055	0.008	0.023	0.003	0.1	0.09	0.11	0.11	0.22	0.06	0.778
D. A+C	0.076	0.009	0.023	0.006	0.1	0.09	0.11	0.11	0.22	0.06	0.803

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 (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.

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.]

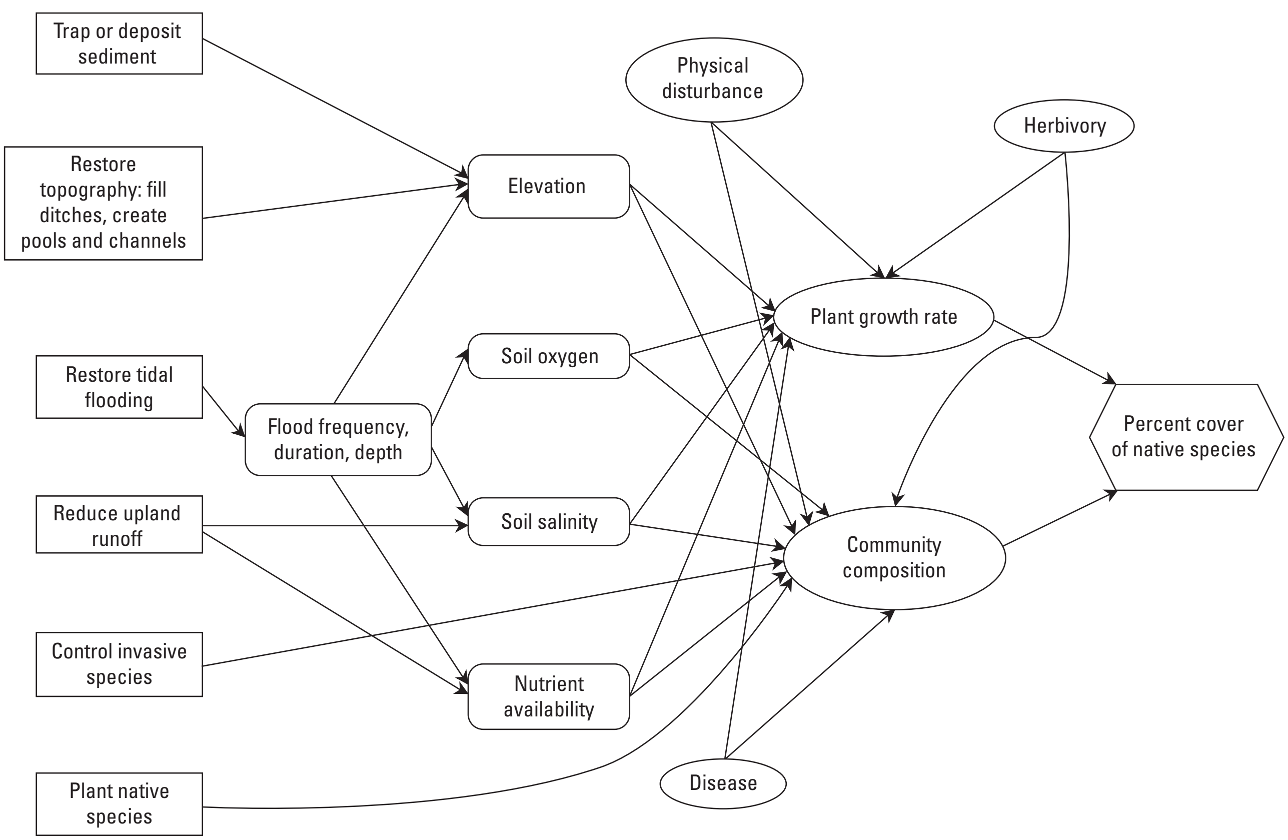


Figure 1.1. Influence diagram used to estimate percent cover of native vegetation in response to implementing certain management actions.

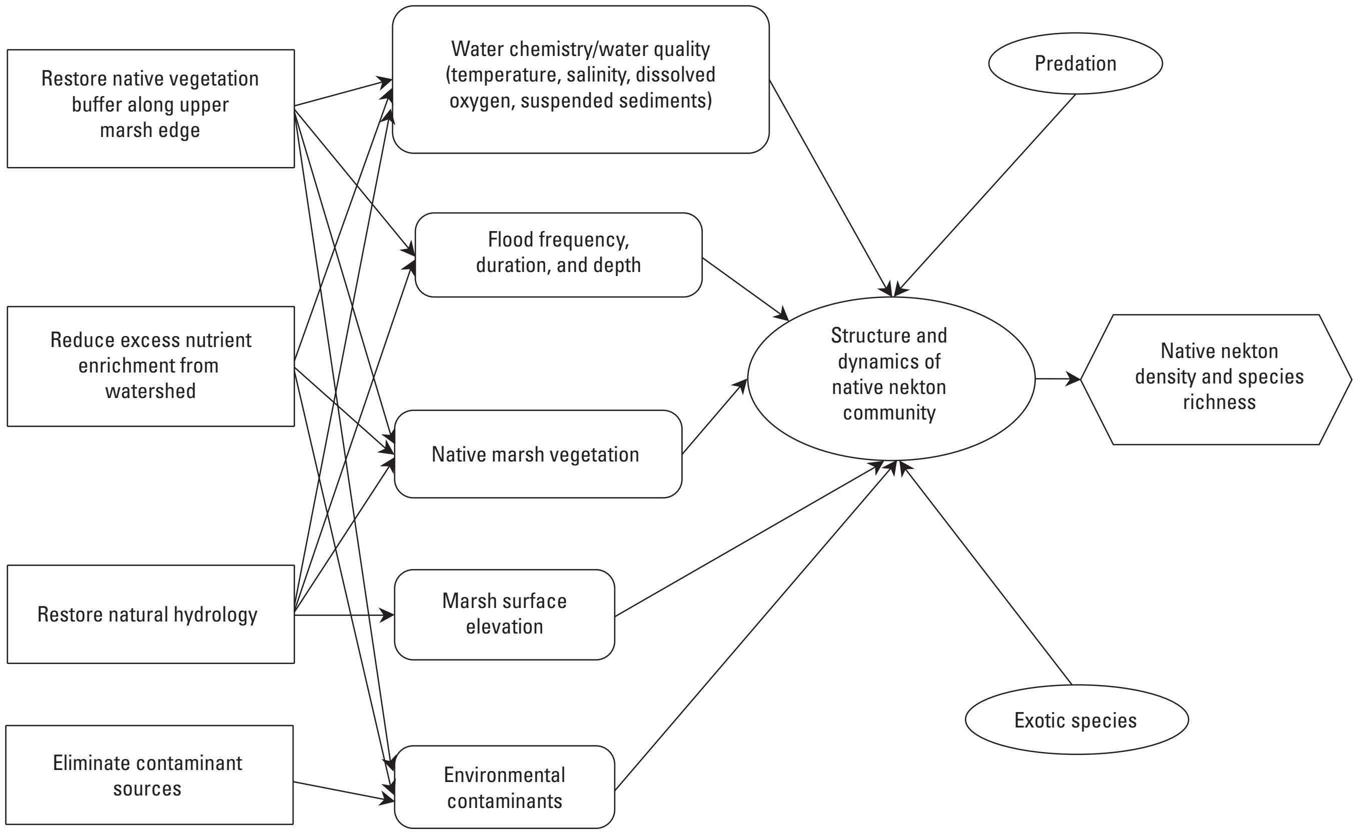


Figure 1.2. Influence diagram used to estimate nekton density and species richness in response to implementing certain management actions.

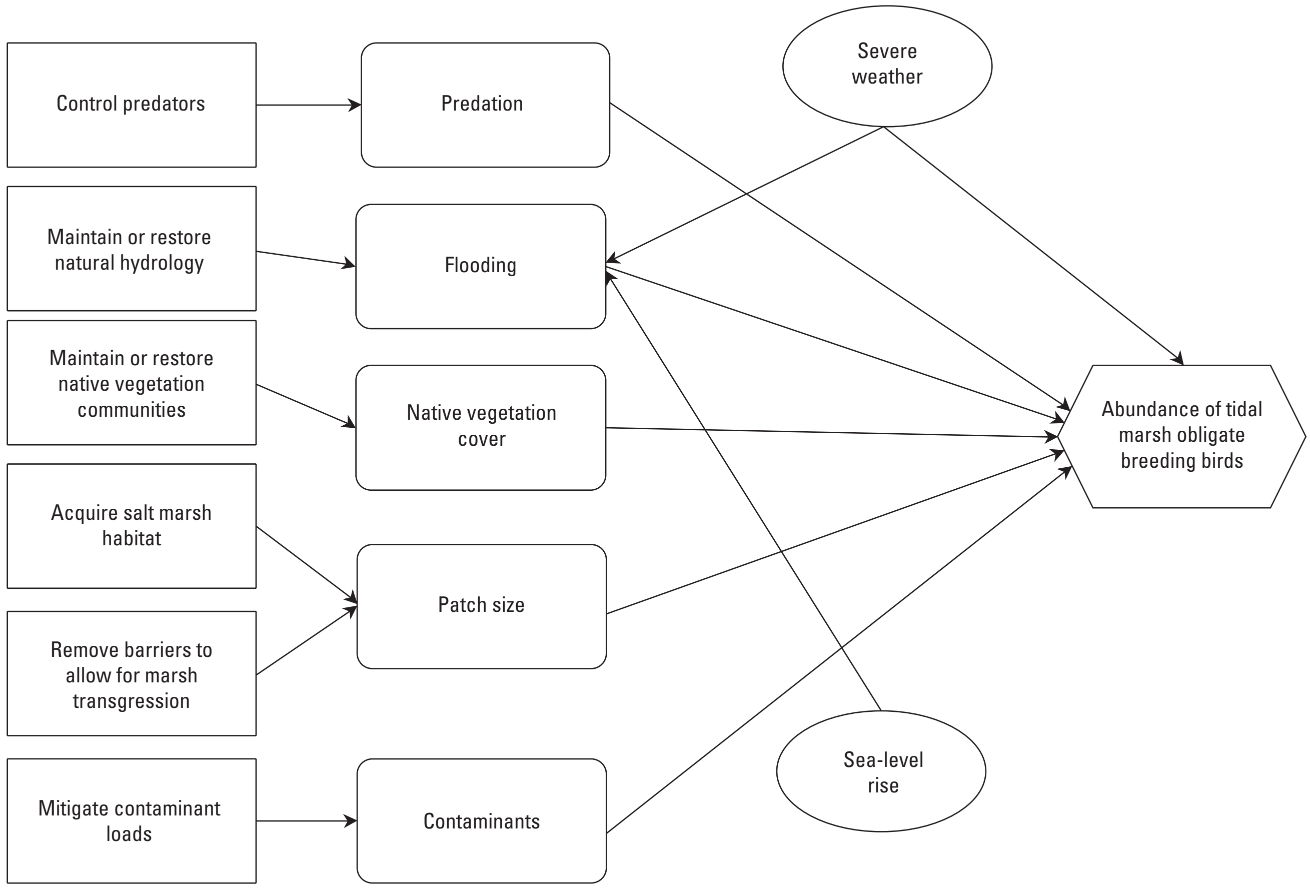


Figure 1.3. Influence diagram used to estimate abundance of tidal marsh obligate breeding birds in response to implementing certain management actions.

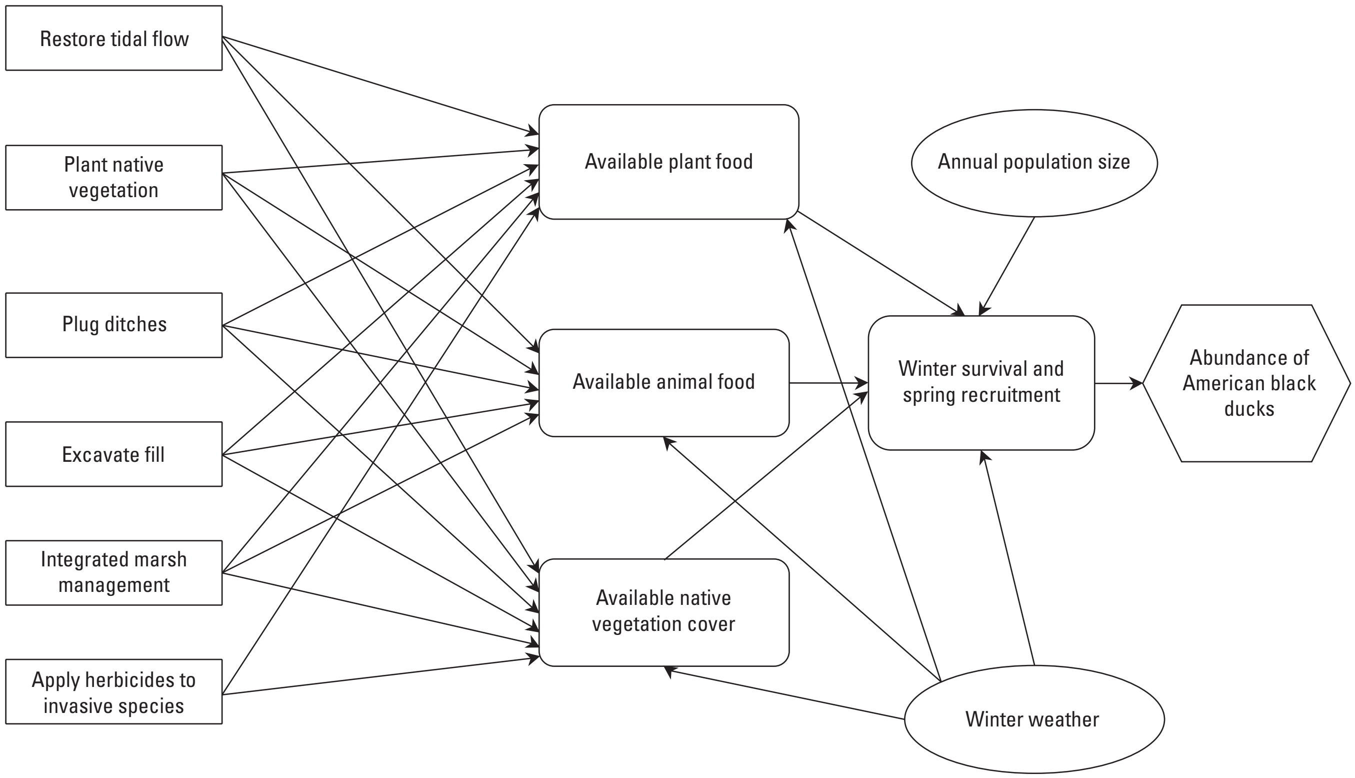


Figure 1.4. Influence diagram used to estimate abundance of American black ducks in winter, as indicator species for nonbreeding wetland birds, in response to implementing certain management actions.

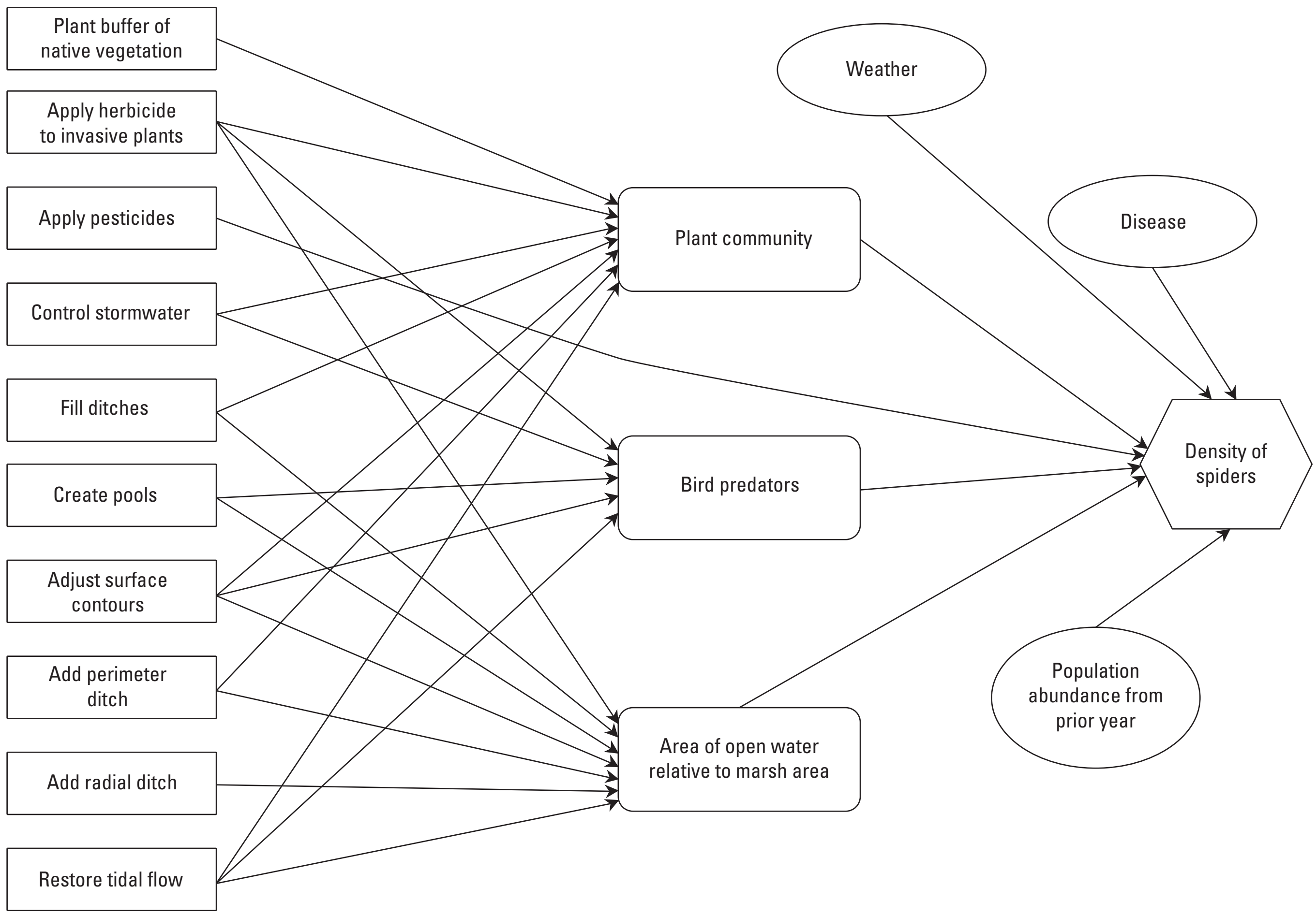


Figure 1.5. Influence diagram used to estimate density of spiders, as indicator of trophic health, in response to implementing certain management actions.

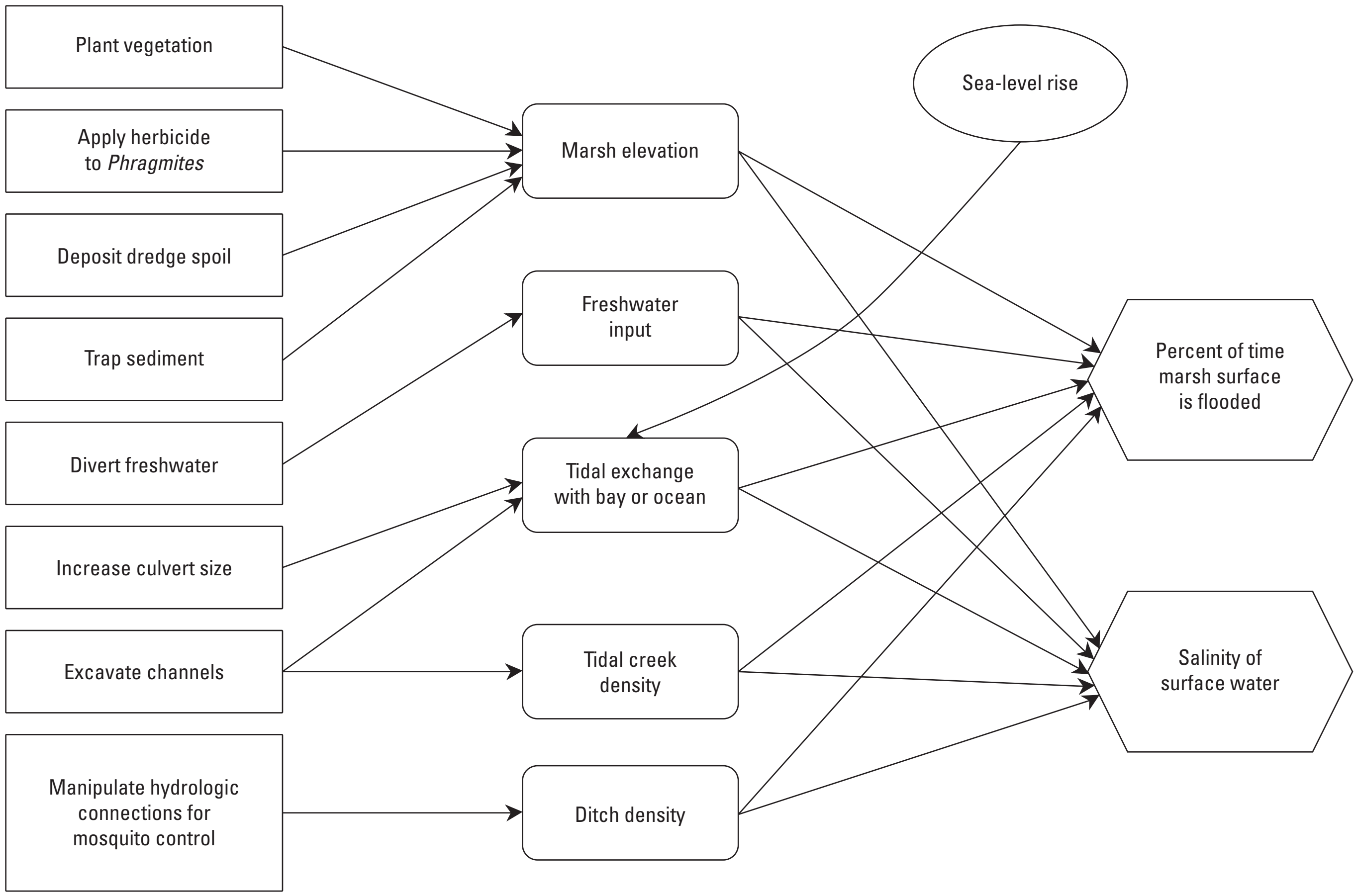


Figure 1.6. Influence diagram used to estimate percent of time marsh surface is flooded and salinity of marsh surface water in response to implementing certain management actions.

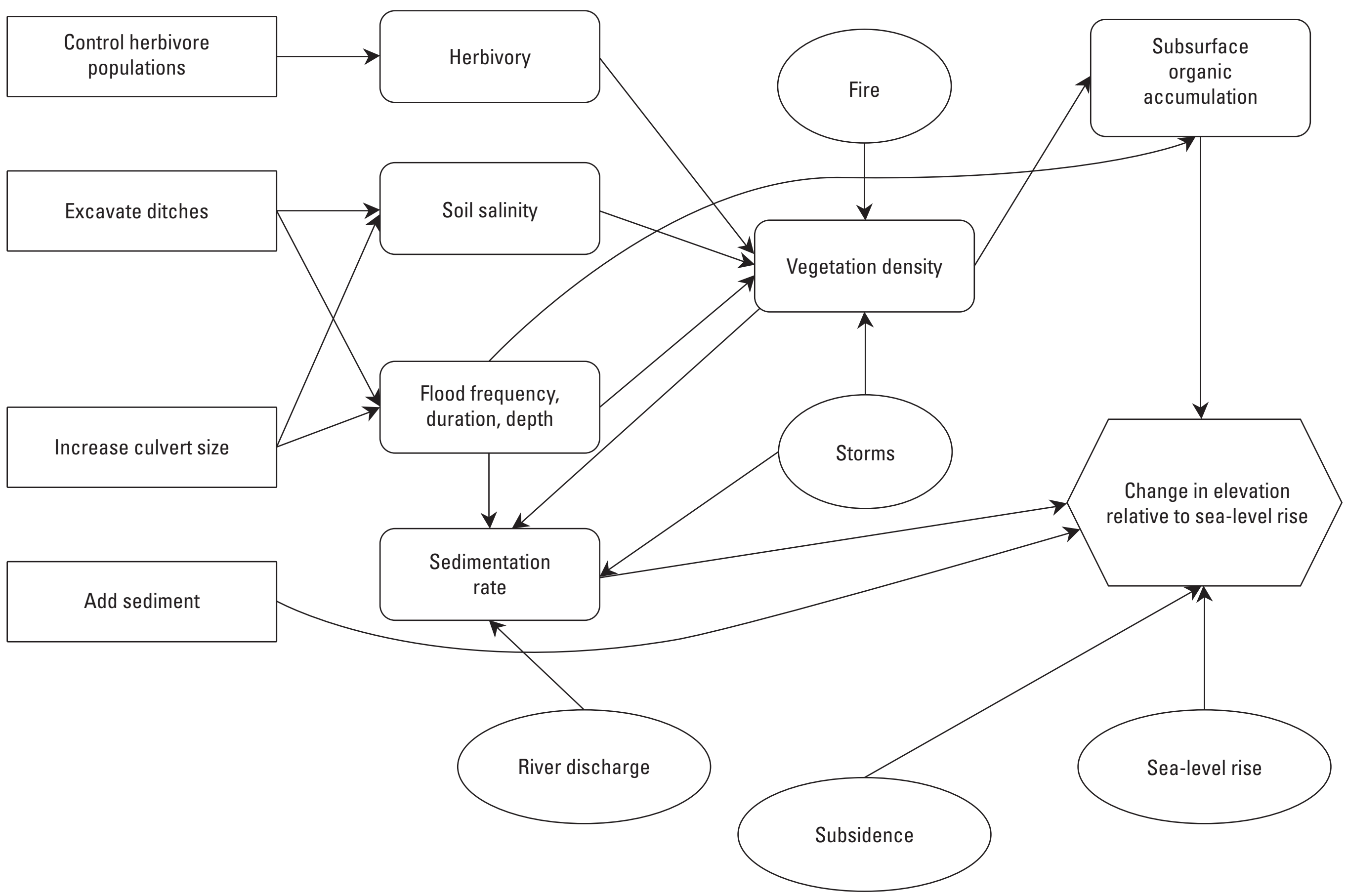


Figure 1.7. Influence diagram used to estimate change in elevation of the marsh surface relative to sea-level rise in response to implementing certain management actions.

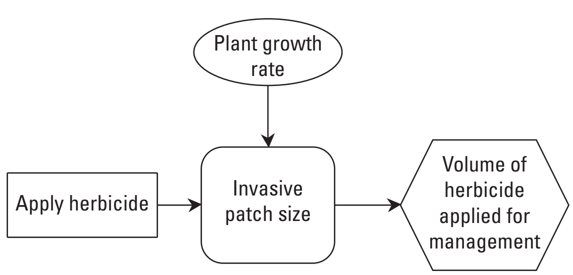


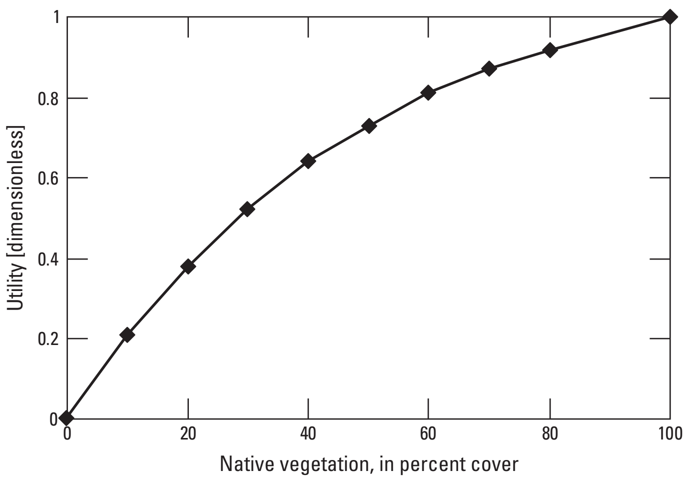
Figure 1.8. Influence diagram used to estimate volume of herbicide that would be applied if decision was made to use chemical control for removing unwanted vegetation.

Appendix 2. Utility Functions for the Cape May and Supawna Meadows National Wildlife Refuges

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 through 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 Cape May and Supawna Meadows National Wildlife Refuges; 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.

Reference Cited

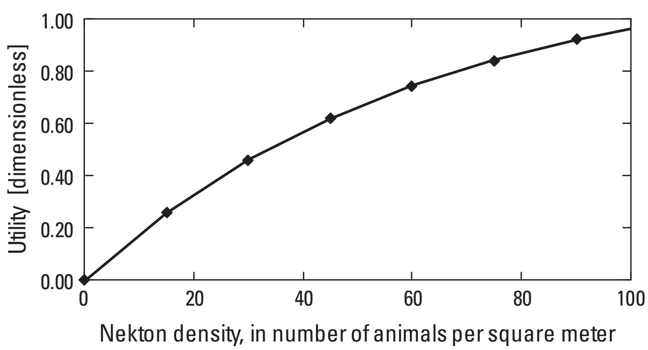
Neckles, H.A., Lyons, J.E., Guntenspergen, G.R., Shriver, W.G., and Adamowicz, S.C., 2015, Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems: Estuaries and Coasts, v. 38, no. 4, p. 1215–1232. [Also available at https://doi.org/10.1007/s12237-014-9822-5.]



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

where
Low = 0
High = 100
ρ = 50

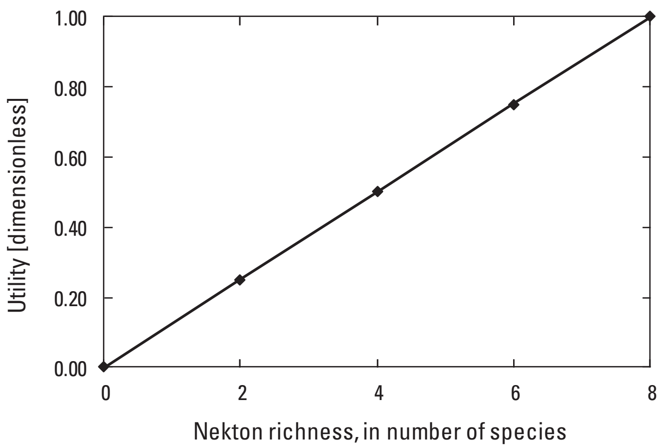
Figure 2.1. Native vegetation at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.



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

where
Low = 0
High = 110
ρ = 63

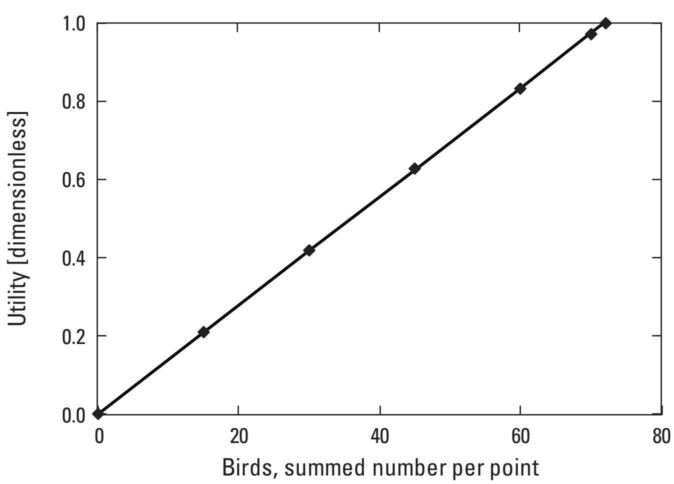
Figure 2.2. Native nekton density at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.



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

where
Low = 0
High = 8

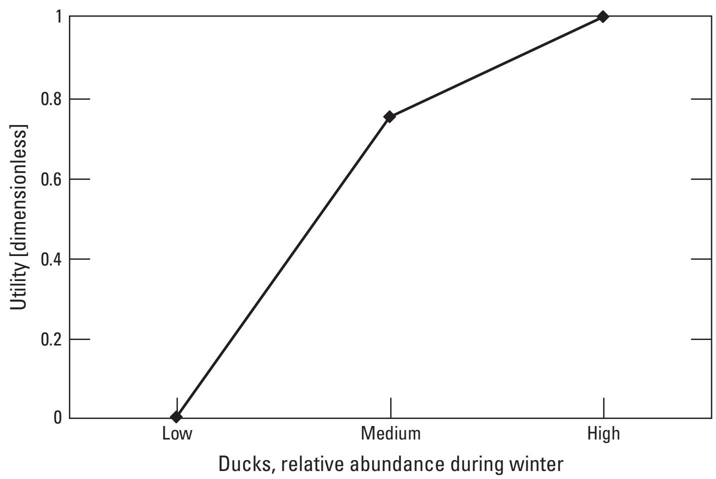
Figure 2.3. Native nekton species richness at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.



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

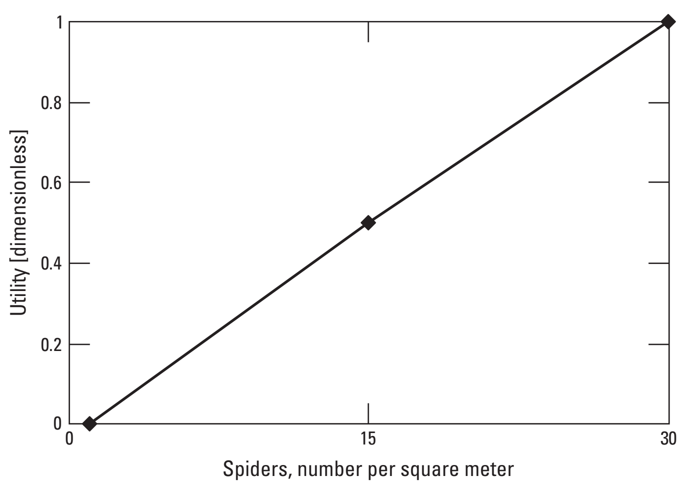
where
Low = 0
High = 72

Figure 2.4. Tidal marsh obligate birds at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.



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

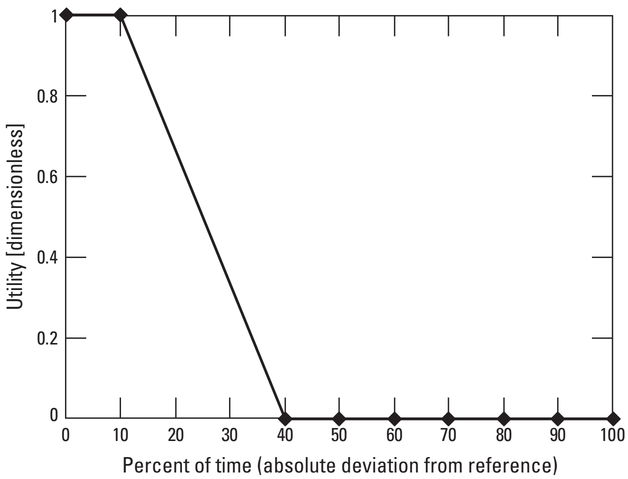
Figure 2.5. American black ducks at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.



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

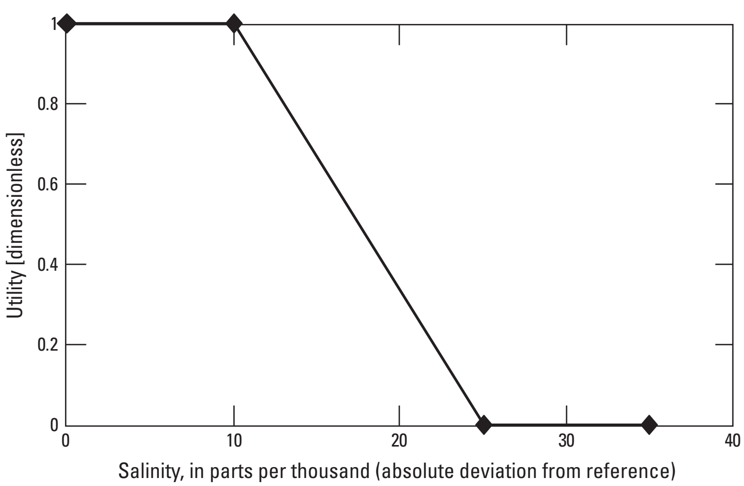
If $x > 15$, then $u(x) = 0.5 + (0.5 \times \frac{x-15}{15})$

Figure 2.6. Marsh spiders at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.



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 Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.



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 Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.

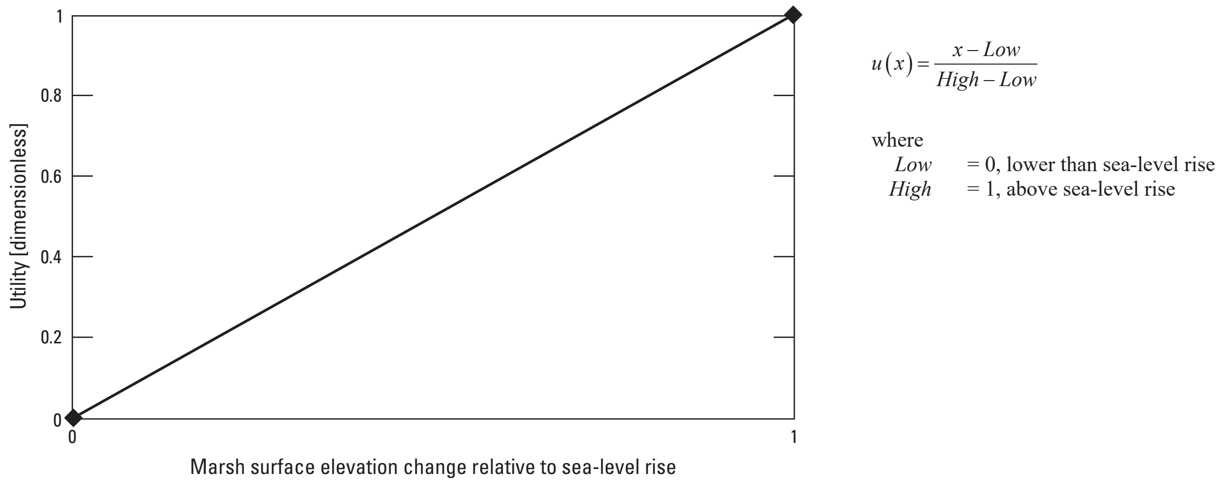


Figure 2.9. Change in marsh surface elevation relative to sea-level rise at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.

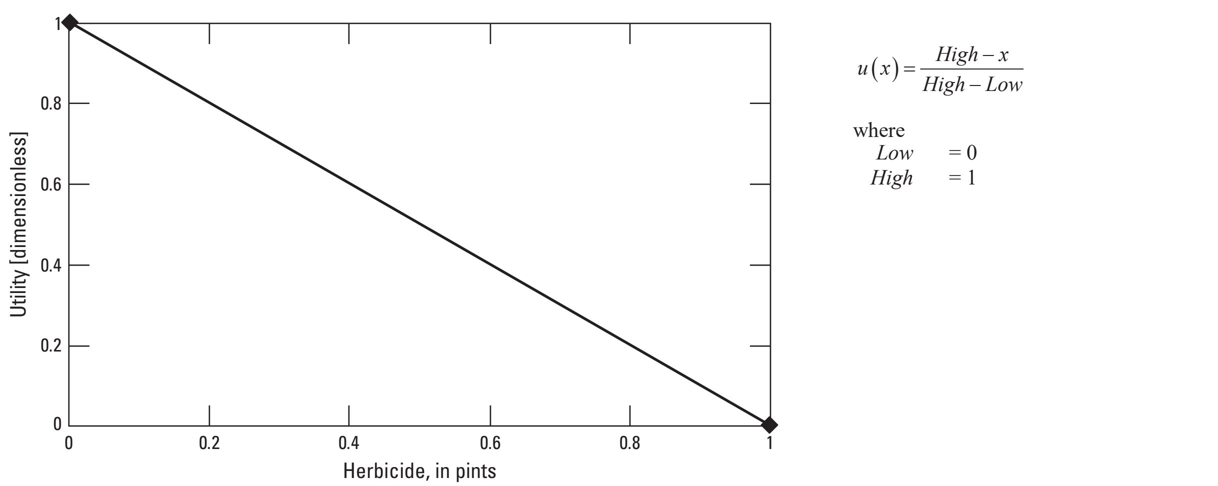


Figure 2.10. Application of herbicides at the Cape May and Supawna Meadows National Wildlife Refuges, New Jersey.

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