Appendix 1. Supplementary information regarding a structured decision making (SDM) process to inform management of tidal marshes in San Francisco Bay (SFB), California USA.

METHODS

Study Area

A tremendous amount of information is available on the internet about the San Francisco Bay estuary including tidal marshes. For detailed maps and information about SFB (see http://www.sfei.org/content/ecoatlas_habitats, EcoAtlas of Baylands).

Problem framing:

Guidelines for workshop were to: (1) limit the number of expert panelists to 10-15; (2) require them to attend the entire 5-day session; and (3) preferentially invite resource managers, planners, and policy makers over scientists to focus more on defining the management questions and objectives.

We then developed a series of questions related to our problem statement:

- When and where should restoration or adaptation occur?
- How do we evaluate cost-effectiveness of actions?
- Is there a way to maximize or optimize benefits?
- What are the considerations of time and spatial scales for this problem?
- How do we compare the cost of restoration with the wetland benefits and services gained over the short- and long-term?
- Should we focus on preserving existing marshes or on creating or re-establishing them?
- Should there be a focus on particular target species?

RESULTS

Consequences

With the exception of human benefits that were only evaluated for 2020, the fundamental objectives were evaluated at both the 2020 and 2050 time horizons. In addition to simplifying the decision model, focusing solely on the shorter-term horizon for human benefits is consistent with the limited timeframe for projections of human health due to coastal hazards under climate change.

We assigned a measureable attribute to each objective along with external factors so that consequences of alternative management strategies could be evaluated (Table A1.1, Main Document Table 2). For likelihood of recovering endangered species, we chose as an example the California Ridgeway's Rail (henceforth Clapper Rail; *Rallus obsoletus obsoletus*), a federally endangered and secretive marsh bird that is representative of species requiring mid to high-elevation tidal marsh. For recovery of the Clapper Rail, we used the likelihood of meeting its habitat requirements defined in the tidal marsh recovery plan (USFWS 2009).

To incorporate important tidal marsh ecosystem services in the decision analytic framework we developed two multi-attribute indices (Main Document Table 2). First, an index of marsh ecosystem integrity was based on five attributes including the area of marsh within three elevation classes (i.e., low, mid, and high), native plant species richness, and accretion rate. Our marsh ecosystem index (0 to 5) was the sum of scores for the five individual ecosystem attributes; each ecosystem attribute received a score of 0 to 1 where 1 was the most desired outcome. The marsh ecosystem index was developed to be independent of Clapper Rail habitat requirements. Second, an index of human benefits incorporated three attributes including the incidence of mosquito-borne diseases, condition of human infrastructure with respect to flooding, and recreational opportunities in tidal marshes. As with the marsh integrity index, each attribute of the human benefits index received a score of 0 to 1 for least to most desirable and was then summed for a total human-benefit score of 0 to 3. When modeling outcomes resulting from the alternative management strategies with respect to the fundamental objectives at each time horizon, we accounted for uncertainty regarding the available budget and the annual frequency of intense storms (Table A1.2).

Our BDN was comprised of 10 nodes, including a utility node, a decision node, and 8 stochastic nodes (Main Document Figure 4; Table 2). The Netica file containing the BDN can be accessed in Appendix 2. Of the stochastic nodes, one represented external storms and two represented operating budgets under two time frames (i.e., 2012-2020 and 2020-2050). SLR was treated as a constant linear increase in this prototype due to the shorter time horizon and because SLR is expected to have a gradual increase through 2050. Five of the other stochastic nodes represented fundamental objectives regarding Clapper Rail recovery, marsh ecosystem integrity, and human benefits. The remaining stochastic node was the budget from 2021-2050, which represented the only means objective in the network. Predictor variables were represented by arrows going into each stochastic node within the BDN (Main Document Figure 5). To our knowledge, there were no mathematical predictive models available to parameterize the probabilistic relationships in our BDN. For the purposes of rapid prototyping and in minimizing the required predictions to elicit from the panel, we discretized the continuous stochastic nodes for the analysis into two categories each (Main Document Table 4).

For a baseline parameterization of our BDN, we elicited expert judgments from stakeholders and scientists on the panel for quantifying the likelihood of optimistic and pessimistic scenarios for external influences along with the likelihood of possible outcomes for the objectives. These likelihoods were entered in probabilistic contingency tables for each of the 8 stochastic nodes. For the external factors, the contingency table had just one probability for each of the two possible levels representing belief weights that sum to 100 and represent alternate hypotheses about the magnitude of these factors. The objectives, however, required specification of a larger set of probabilities for their predicted outcomes. For example, there were 2×2×2×5=40 possible combinations of predictor states for the 2050 marsh ecosystem index, which was a function of the 2020 marsh ecosystem index, 2021-2050 budget, frequency of storms, and the allocation strategy, respectively. For each of the possible predictor states regarding the 2050 marsh ecosystem index, each expert was asked to assign a probability that the marsh ecosystem index would be 0-3 as opposed to 4-5.

Consistent with the Delphi method stakeholders and scientists on the panel provided independent predictions for stochastic nodes representing fundamental objectives with the exception of human benefits at 2020, which were elicited by consensus across the panel for the sake of rapid prototyping. Likewise, predicted likelihoods for levels of storms and budgets were elicited as a group. For probabilities that were elicited individually, we evaluated the logical consistency of the original elicited predictions from each panel member. For example if probability of Clapper Rail recovery was 0.9 when assuming low frequency of intense storms, then probability of rail recovery under high frequency of intense storms must be ≤ 0.9 because of the potential negative (but not positive) impacts of storm events on rail habitat. Whenever such logic was violated, we corrected the probabilities to ensure logical consistency. Elicitation fatigue is an important source of bias when experts are asked to provide many predictions in a short period of time.

Summary statistics of individually elicited and corrected predictions were provided to the expert panel. Panel members were then offered the opportunity to revise their predictions in light of these, but in our case, none of them did so. In addition to incorporating elicited predictions as a baseline parameterization, the BDN allowed for sensitivity analyses to examine the relative importance of alternate sources of uncertainty about management effectiveness and environmental dynamics (see **Sensitivity analyses**).

Tradeoffs and optimization

An important element of our decision analysis was accounting for tradeoffs among multiple fundamental objectives. To quantify these tradeoffs, we asked the panel of decision-makers and stakeholders to independently express a utility value representing their relative preference for each of the $2^5=32$ possible outcomes across the five measures for the fundamental objectives (Table A1.2). Fundamental objectives were represented in our BDN by stochastic nodes with arrows connecting to the utility node (Main Document Figure 4). Utility values were elicited on a scale from 0 to 100, where 0 represented the least favorable and 100 the most favorable outcome. Taken as an example, we asked each team member to assign a utility value to the possible outcome where marsh integrity is low in 2020 but high in 2050, California clapper rail is not recovered in 2020 nor 2050, and human benefits are low in 2020. Panelists filled out their utility value then for every possible outcome with respect to the five fundamental objectives.

Again consistent with the Delphi method, stakeholders on the panel were asked to independently assign their utility values to alternative outcomes in terms of the fundamental objectives. Likewise, we offered stakeholders the opportunity to revise their utilities following a group discussion, but none did. To arrive at a consensus utility value for each possible outcome, we presented participants with summary statistics on each set of elicited utility values across team members. As with the predictions (see **Consequences**, above), panelists were offered to modify their elicited utility value following a group discussion, but they were satisfied with the original values and declined. As with the predicted probabilities, we evaluated the logical consistency of the original elicited utilities from each stakeholder. For example if a stakeholder assigned a utility of 10 to a case where all outcomes were pessimistic except for human benefits, then all cases with an optimistic outcome for human benefits should receive a utility of ≥10. Whenever such logic was violated, we corrected the utilities to ensure logical consistency. The panelists agreed to use the average of the final elicited utilities across all experts to reflect the utility of a given potential outcome, giving equal weight of importance to each expert. We used the upper and lower 95% confidence intervals among elicited utilities for computing the corresponding upper and lower 95% confidence intervals for expected utilities among alternative allocations to account for the variation in utilities among experts.

We used Netica to compute the expected utility for each of the allocation strategies based on the elicited likelihoods of external effects and predicted outcomes along with the elicited utility values. The expected utility from an allocation was the value a decision maker would expect to realize following implementation of that allocation and was on the same unit scale as the elicited utilities, which ranged 0-100. The maximum expected utility across alternative allocations then indicated the optimal decision.

Sensitivity analyses

We conducted two sets of one-way sensitivity analyses where we adjusted one factor at a time within the BDN to investigate its effect on decision-making. First, we evaluated how expected utilities, and therefore how the optimal decision, changed under alternative assumptions representing knowledge about the system. For this purpose we toggled predictions one at a time between their low and high values for each of the stochastic nodes representing external factors and objectives. After each perturbation, expected utilities were recalculated. For example for the Clapper Rail perturbation, we computed the expected utilities when Clapper Rails were assumed to be recovered by 2020 and computed the expected utilities again assuming rails were unrecovered by 2020 while all other stochastic nodes retained their baseline parameterization. Across the 8 stochastic nodes, we conducted 16 perturbations. If the strategy that was optimal under the baseline parameterization still had the maximum expected utility following perturbations of a particular node, then we concluded the decision was robust to that source of uncertainty. Otherwise, we concluded the decision was sensitive to that stochastic node.

Second, we examined how expected utilities changed under alternative scenarios regarding the utility values placed on potential outcomes. To this end we constructed alternative scenarios representing three types of advocacy, with each advocacy scenario corresponding to one of three focal fundamental objectives. The advocacy scenarios were developed to illustrate the potential for a stakeholder campaign to advocate a preference for a particular objective and how this would change the optimal decision, if at all. For example, Clapper Rail Advocacy was constructed to illustrate the consequences of hypothetically enhancing stakeholder preference for long-term Clapper Rail recovery over the other objectives. To represent this scenario, we selected the maximum utility across participants for each possible outcome where the Clapper Rail is recovered by 2050 and the minimum utility for outcomes when rails were unrecovered. This set of modified utilities was then entered into the utility node of the BDN, and expected utilities were recomputed. Scenarios for Marsh Advocacy and Human Benefits Advocacy were constructed in an analogous fashion representing advocacy for long-term marsh integrity and short-term human benefit. These three scenarios provided a contrast to the Status Quo Advocacy, which was represented by the average utility across participants for each potential outcome under the baseline parameterization (Figure A1.1, A1.2).

The optimal allocation was robust when perturbing stochastic nodes or adjusting advocacy scenarios individually (Figures A1.1 and A1.2). Exceptions occurred when conducting a two-way sensitivity analysis by simultaneously assuming the Marsh Advocacy scenario and optimistic scenarios for storms or for marsh integrity at 2020, which resulted in the **Marsh Migration** allocation strategy becoming the optimal decision (not shown in Figure A1.1). Resolving the uncertainty about storm frequency or marsh integrity at 2020 under the Marsh Advocacy scenario would be expected to increase expected utility by an EVPI <0.4 on a scale of 0 to 100. This quantity is the Expected Value of Perfect Information (EVPI), which is the value of resolving a particular source of uncertainty. In cases where perturbations did not change the optimal decision, EVPI equaled zero.

Spatiotemporal linkages

Conservation of coastal ecosystems is complicated not only by socioecological complexity, but also by having decisions that are enacted among numerous spatial units and whose consequences are linked across space and time (Wilson et al. 2011). Our framework was intended as an initial prototype and a case study that considered the entire SFB estuary as a single management unit and temporal allocation options that were prescriptive rather than adaptive. Scaling up the effects of conservation strategies from individual management units to regional scales is a great challenge on its own (Mattsson et al. 2012). Recognizing that biophysical processes and management constraints vary at intermediate subregional scales within SFB (Goals Project 1999), this subregional level may provide a critical lynchpin for linking the local management strategies to regional-scale outcomes. This challenge of linked spatial scales combined with the challenge of developing a matrix of optimal strategies across space and time poses a difficult problem, but one that can be solved with the tools and methods available in the literature and in the SDM toolbox (Conroy and Peterson 2012, Runge et al. 2011, Wilson et al. 2011). A starting point may be to identify optimal strategies to allocate climate restoration actions across space and time through 2050, as the **Climate-Smart Restoration** strategy was optimal under our aspatial decision analytic framework (Runge et al. 2011, Wilson et al. 2011, Conroy and Peterson 2012,). A more robust and transparent strategy would explicitly account for these spatiotemporal linkages in the consequences of decisions for conserving the resilience of the SFB ecosystem and the services it provides.

Table A1.1. Draft objectives that were later refined and condensed for the prototype decision model.

Draft objectives
Increase understanding of climate change forcing on wetland processes‡
Increase understanding of where and how wetlands will migrate and persist‡

Provide transition areas to allow for wetlands to migrate upslope with SLR
Maintain and expand tidal wetlands functions and services in light of future climate change
Increase wetland resiliency against extreme climatic events
Manage tidal wetlands to maximize biodiversity, diversity of wetland types
Recovery of endangered species
Ensure habitat persistence and quality for endangered species
Reduce non-climate stressors to increase resiliency (subset of wetland functions and services)
Maintain human services
Clearly articulate a justification for wetlands protection, management and restoration†
Be open to innovate ideas for restoration and augmentation of wetlands†
Develop engineering methods to sustain marsh plain, such as dredge or upland sediment use
Understand tradeoffs of linked consequences of mud flat, marsh and upland transition‡

†Process objective – a goal to improve the planning process for reaching decisions
‡Knowledge objective – a goal describing the need for information to support making decisions

Table A1.2. Utility values elicited from stakeholder panel. Averages presented as mean ± standard deviation.

Outcome scenarios†					Stakeholder utility values‡									
Marsh Integrity in 2020	Marsh Integrity in 2050	Rail recovery by 2020	Rail recovery by 2050	Human benefits in 2020	1	2	3	4	5	6	7	8	9	Average
low	low	no	no	low	0	0	0	0	0	0	0	0	0	0 ± 0
low	HIGH	no	no	low	5	5	10	20	50	10	40	1	10	17 ± 17

low	low	YES	no	low	10	5	5	20	18	5	20	20	5	12	±	7
low	HIGH	YES	no	low	30	10	15	40	50	10	40	50	10	28	±	17
low	low	no	YES	low	10	6	10	40	45	5	60	20	10	23	±	20
low	HIGH	no	YES	low	30	10	35	50	85	15	70	40	15	39	±	26
low	low	YES	YES	low	20	11	15	50	55	8	75	78	20	37	±	28
low	HIGH	YES	YES	low	50	15	35	70	85	15	80	85	25	51	±	30
low	low	no	no	HIGH	20	5	10	40	10	7	30	5	5	15	±	13
low	HIGH	no	no	HIGH	60	25	45	40	60	13	60	37	10	39	±	20
low	low	YES	no	HIGH	30	20	16	40	18	10	40	70	15	29	±	19
low	HIGH	YES	no	HIGH	70	70	60	50	60	13	65	80	20	54	±	23
low	low	no	YES	HIGH	40	35	25	50	50	7	68	40	15	37	±	19
low	HIGH	no	YES	HIGH	70	70	70	70	85	15	85	70	20	62	±	26
low	low	YES	YES	HIGH	40	50	30	50	55	10	75	80	30	47	±	22
low	HIGH	YES	YES	HIGH	80	75	70	80	85	20	95	90	35	70	±	25
HIGH	low	no	no	low	20	5	20	20	20	5	10	20	40	18	±	11
HIGH	HIGH	no	no	low	40	10	55	50	65	18	50	37	50	42	±	18
HIGH	low	YES	no	low	30	10	16	40	18	5	20	50	40	25	±	15
HIGH	HIGH	YES	no	low	50	15	70	60	65	18	60	60	60	51	±	20
HIGH	low	no	YES	low	30	10	20	50	45	5	65	50	45	36	±	20
HIGH	HIGH	no	YES	low	50	15	60	60	90	25	75	80	70	58	±	25
HIGH	low	YES	YES	low	40	11	50	50	60	8	75	78	50	47	±	25
HIGH	HIGH	YES	YES	low	70	20	95	80	90	25	85	100	80	72	±	29
HIGH	low	no	no	HIGH	60	10	16	50	10	7	45	20	40	29	±	20
HIGH	HIGH	no	no	HIGH	90	55	65	70	65	35	65	37	60	60	±	17
HIGH	low	YES	no	HIGH	60	45	16	50	18	10	55	70	50	42	±	22
HIGH	HIGH	YES	no	HIGH	90	85	85	70	65	50	85	80	70	76	±	13
HIGH	low	no	YES	HIGH	80	65	60	50	80	10	68	70	60	60	±	21
HIGH	HIGH	no	YES	HIGH	90	95	95	80	100	75	95	80	70	87	±	11
HIGH	low	YES	YES	HIGH	80	65	75	80	80	10	90	90	60	70	±	25
HIGH	HIGH	YES	YES	HIGH	100	100	100	100	100	100	100	100	100	100	±	0

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†Outcomes presented as binary levels of five attributes of fundamental objectives including an index of marsh integrity, recovery of California clapper rail, and an index of human benefits from tidal marshes.

‡Utility values for the worst-case and best-case scenarios were fixed at 0 and 100, respectively. Stakeholder identities are anonymized to protect their anonymity. One member recused themselves from the elicitation.

Figure A1.1. Changes in expected utilities based on a one-way sensitivity analysis among four advocacy scenarios for conservation and restoration of tidal marshes in San Francisco Bay through 2050. Three advocacy scenarios (A-C) were represented by choosing one of nine elicited utility values among stakeholders for each outcome. For example, in the Clapper Rail Advocacy scenario (A), the maximum utility among experts was chosen for each outcome where the California clapper rail was recovered in 2050, otherwise the minimum utility was chosen. This method was used to select a set of perturbed utilities that were used to generate the expected utilities for alternative strategies under each advocacy scenario. In graph D, each bar height and whisker represents the mean and 95% confidence interval estimated from the distribution of elicited utilities among stakeholders. No whiskers are shown in the remaining graphs, as they each represent a single set of perturbed utility values. The **Climate-Smart Restoration** allocation strategy had the highest expected utility among the alternatives under all four advocacy scenarios.

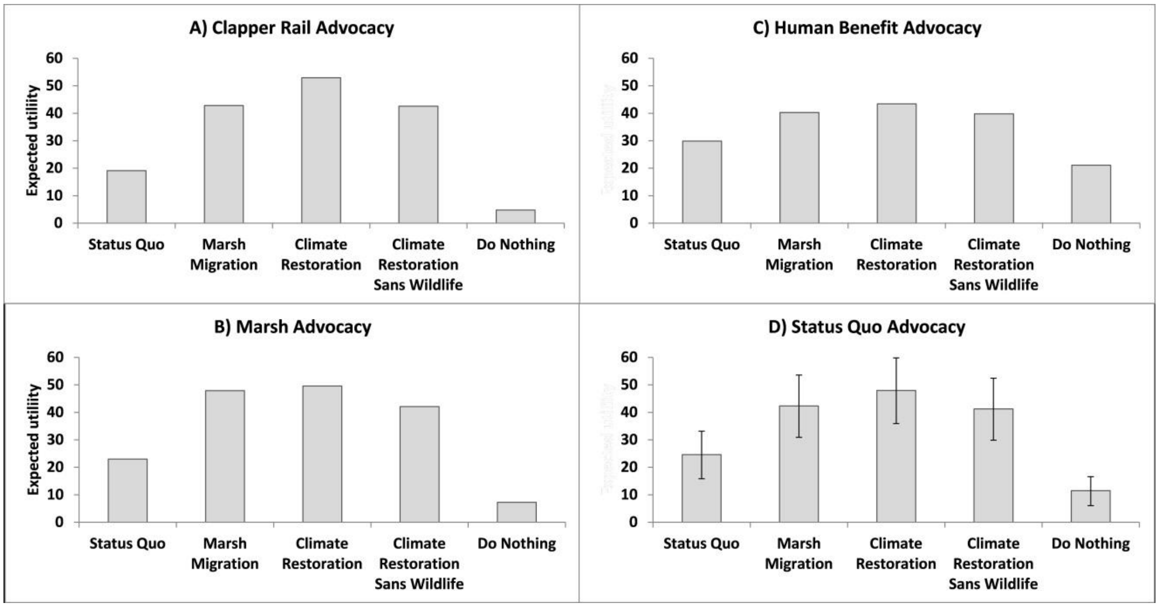

Figure A1.2. Changes in expected utilities based on a one-way sensitivity analysis among contrasting assumptions regarding predictions for stochastic nodes in a Bayesian decision network to inform conservation and restoration of tidal marshes in San Francisco Bay. Bar heights were based on a baseline parameterization of the stochastic nodes; the perturbed node is identified at the top of each graph. Upper dashed line and lower solid lines represent optimistic and pessimistic perturbations of the predictions, respectively.