

Climate change and tidal marsh restoration in San Francisco Bay: should we restore more marshes to full tidal action and how should they be prioritized?

A Case Study from the Structured Decision Making Workshop

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The Decision Problem

Climate change impacts for coastal ecosystems include projected changes in mean and extreme ambient temperatures, precipitation patterns, ocean temperature and acidity, extreme storm events and sea-level rise (Cayan *et al.* 2005; Hansen *et al.* 2006; IPCC 2007). Recent sea-level rise (SLR) projections range from 0.57 to 1.1 m (Jevrejeva *et al.* 2012) or 0.75 to 1.9 m by Grinsted *et al.* (2010) and Vermeer and Rahmstorf (2009) by 2100, which are contingent upon the ambient temperature conditions. The expected accelerated rate of SLR through the 21st century will put many tidal salt marsh ecosystems at risk, especially those in topographically low-gradient areas (Takekawa *et al.* 2006). Perhaps equally important, but poorly understood are

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the impacts from increased storm frequency and intensity. Increased sea levels (Nicholls and Cazenave 2010) with increased storm frequency and/or intensity (Cayan *et al.* 2008) may pose the greatest threat to the near-term sustainability of tidal marsh wildlife. San Francisco Bay (SFB) estuary supports a large proportion of the remnant tidal marshes on the Pacific coast of North America (Greenberg *et al.* 2006). Within this urbanized estuary (Nichols *et al.* 1986), the marshes are recognized as highly-threatened habitats with restoration efforts ongoing. More than 80% of the historical marshes have been lost in SFB since the mid-1800s (Goals Project 1999), but in the past three decades extensive efforts have been made to restore or rehabilitate areas. However, the benefit of these restoration efforts over the long-term may be reduced if marsh accretion is unable to keep pace with local SLR. Here, using the Structured Decision Making process a team of participants from public agencies in the SFB estuary who preserve, manage, or restore tidal marshes defined and worked through an initial question “Climate change and tidal marsh restoration in SFB: should we restore more marshes to full tidal action and how should they be prioritized?” and developed a first decision prototype. Throughout a sensitivity analysis, the Status Quo Allocation and Do Nothing produced the lowest utility values. The Climate Restoration Allocation provided the largest utility value, followed closely by the Marsh Migration Allocation.

Introduction

Background

Sea-level rise and an increase in extreme storm events will be the most significant factors threatening coastal ecosystems and their dependent biodiversity (IPCC 2007). Coastal ecosystems are vulnerable to climate change with increased flooding from sea-level rise and accompanying changes in storm frequency and intensity, which will increase inundation and coastal erosion (IPCC 2007; Kirwan and Murray 2007; Solomon *et al.* 2009). Changes in ocean temperature, local freshwater delivery, and ocean acidification also have potential negative impacts on coastal ecosystems (Nicholls and Cazenave 2010; FitzGerald *et al.* 2008, IPCC 2007). Global sea level has risen an average of 1.8 mm/year between 1961 and 1993, and more recently 3.1 mm a year since 1993 (IPCC 2007). Projections range from 0.19 to 0.58 m (IPCC 2007), 0.6 to 1.6 m (Grinsted *et al.* 2010, Jevrejeva *et al.* 2010, Jevrejeva *et al.* 2012), or as much as 1.9 m by 2100 (Vermeer and Rahmstorf 2009). However, uncertainty exists for projections of mean sea-level rise by 2100 (*see* Breaker and Ruzmaikin 2011). Warmer sea surface temperatures have increased the number and proportion of storms, particularly hurricanes, since 1970 (Emanuel 2005; Webster *et al.* 2005). Storms pose significant threats to coastal areas from water level surges, sustained winds, and large amounts of rainfall in a short period of time (Mousavi *et al.* 2011).

San Francisco Bay (SFB) is the largest estuary on the Pacific coast and is an important site for migratory birds and endemic tidal marsh wildlife (Takekawa *et al.* 2006) and also is home to over 8 million people (Goals Project 1999). In 1850, tidal marsh covered an estimated 2,200 km² (Atwater *et al.* 1979), but fragmentation and modification through local- and watershed-scale land use changes resulted in loss of >80% (Goals Project 1999). In this highly urbanized region (Nichols *et al.* 1986), endemic tidal marsh species are negatively affected by habitat and population fragmentation, increased predation from human associated nuisance species, invasive species, and pollution among other stressors. Yet over 90% of the remaining coastal wetlands in California are found in the SFB estuary. Sea level has risen 19.3 cm between 1900 and 2000 in SFB (Cayan *et al.* 2006), with future projections up to 1.4 m for California by 2100 (Cayan *et al.* 2009). The SFB estuary currently has 310 km² of baylands vulnerable to 100-yr storm floods, however most of those lands are behind levees (Knowles 2010). Future storm projections suggest that a 50 cm SLR will increase vulnerability of baylands by 20% (372 km²) from storm surges and a 150 cm SLR will increase vulnerability to 60% (495 km²) (Knowles 2010).

Ecological context

These fragile and important tidal marsh ecosystems of SFB have endured over 150 years of degradation by humans, resulting in the listing of endangered and threatened species and the establishment of protected areas (e.g. Don Edwards San Francisco Bay National Wildlife Refuge, Napa-Sonoma Marshes Wildlife Area). In 2009, the U. S. Fish and Wildlife Service released a draft plan for tidal marsh ecosystem recovery in central and northern California (USFWS 2009). This plan includes recovery objectives for five endangered species and 11 species of concern over a 50-year planning period. SFB comprises the single largest area of remnant tidal marshes supporting these species (Takekawa *et al.* 2006). For example, many such as the San Pablo song sparrow (*Melodia melodia samuelis*), salt marsh common yellowthroat (*Geothlypis trichas sinuosa*), state-threatened California black rail (*Laterallus jamaicensis coturniculus*), and the federally endangered salt marsh harvest mouse (*Reithrodontomys raviventris*) and California clapper rail (*Rallus longirostris obsoletus*) reside in SFB and are local endemic protected species (Takekawa *et al.* 2011, USFWS 2009). In recent years, efforts have been made to reverse losses of marsh habitat with restoration. Projects span the estuary and include the large restoration program to restore salt ponds in the southern (<http://www.southbayrestoration.org/>) and northern regions of SFB. The San Francisco Bay Joint Venture Project Database Online System for Tracking (POST; <http://www.sfbayjv.org/resources.php>) shows for 2011 as many as 200 estuarine habitat projects aimed at protection, enhancement, or restoration of tidal wetlands. In addition, these tidal marsh habitats provide invaluable recreational activities (e.g. birding, hunting) and buffers from flooding for coastal communities.

Legal, regulatory, and political context

Under federal policy, the U. S. Fish and Wildlife Service (USFWS) have authority for land acquisition and management from a variety of public laws. Examples include the National Wildlife Refuge System Administration Act of 1966 as amended, the National Wildlife Refuge System Improvement Act of 1997, the Endangered Species Act, the Migratory Bird Treaty Act of 1918, the Fish and Wildlife Coordination Act, the Fish and Wildlife Act of 1956, and the North American Wetlands Conservation Act of 1989. In addition to federal guidance, similar policies and authorities exist for land managers under state and local governments. Protection of fish and migratory wildlife species comes under the jurisdiction of the USFWS and the National Oceanographic and Atmospheric Administration National Marine Fisheries Service, while non-migratory species are protected by the state. The Clean Water Act provides protection of wetlands and is a responsibility of the U. S. Army Corps of Engineers (USACE) and U. S. Environmental Protection Agency (EPA) as well as the FWS.

Assumptions

For feasibility in the Structured Decision Making process we chose to make some general assumptions while working through the problem. In general, we made the following assumptions:

1. Global climate change will cause increases both in SLR and extreme events in SFB, however the timing and extent are uncertain.
2. The California Climate Change Center state report (Cayan *et al.* 2006, 2008) was the best guideline for the timing and extent for SLR and storm impacts over the next 90 years.
3. Tidal marsh restoration that enhances existing plant and wildlife communities is beneficial.
4. The long-term effects of climate change on wetland resiliency in SFB are not clear.

Workshop Format

The USFWS National Conservation Training Center and USGS Patuxent Wildlife Research Center organized a Structured Decision Making (SDM) workshop (ECS3159) in Sacramento, California from 17-21 October 2011, which was hosted by the California Landscape Conservation Cooperative (CALCC). SDM is an approach to solving problems based in decision-theory and risk analysis. It provides a flexible framework to breakdown problems and explicitly integrates policy and science to reach decisions that identify and achieve fundamental objectives (Hammond *et al.* 1999). Steps under the SDM framework include assessing the Problems, Objectives, Alternatives, Consequences and Tradeoffs (PrOACT; Hammond *et al.*

1999). Prior to the workshop, a request for proposals was circulated to identify natural resource problems that could be addressed with the SDM process. The USGS Western Ecological Research Center submitted a case study on addressing uncertainties about restoration of tidal marshes in the face of climate change as a follow-up to their recent research supported by the USGS National Climate Change and Wildlife Science Center and the CALCC on potential threats of climate change to tidal marshes and endemic wildlife in SFB. The proposal was accepted as a case study, and a list of participants representing a broad set of SFB decision makers, regulators, and funders focused on conservation were invited to participate in the workshop. During the 5-day workshop, we used the SDM approach to address the challenges of conserving and restoring tidal marshes in light of future climate change impacts.

Guidelines for participants were established by the SDM workshop program to: (1) limit attendance to about 10 members; (2) require participants to attend the entire 5-day session; and (3) preferentially invite managers and decision makers over scientists to define the management questions. On the basis of these guidelines, we coordinated with the CALCC to invite a team of managers, planners, and biologists from a wide array of public agencies in the SFB estuary who preserve, manage, or restore tidal marshes. The final participants represented a cross-section of agencies involved in tidal marsh restoration and management (Table 1). To clarify terminology used in this report we have included a definition section at the end.

Decision Structure

Decision Makers

Identifying the decision makers is a critical element of the SDM process (Hammond *et al.* 1999). However, tidal marsh restoration in SFB is a broad collaboration of many different entities, from local to federal agencies and non-governmental organizations to private landowners. For example, different groups working on tidal marshes may be involved in the many phases of decision-making, including regulation (USFWS Ecological Services, USACE, BCDC, SFB Regional Water Quality Control Board, EPA), planning and funding (SFBJV, SCC, South Bay Salt Pond Restoration Project), restoration design (PWA-ESA and other private consulting firms), land management (FWS Refuges, CDFG Wildlife Areas, CDFG Ecological Reserves, NPS, East Bay Regional Parks), and research (USGS, universities, PRBO Conservation Science, San Francisco Bay Bird Observatory). In our case there was not a single, individual institutional decision-maker for SFB tidal marsh restoration, management and protection.

We chose to use the San Francisco Bay Joint Venture (SFBJV), a 15 year multi-stakeholder conservation partnership as a decision-making entity for tidal marsh restoration in SFB. The SFBJV was established in 1996 as one of 18 Joint Ventures under Department of Interior funded Migratory Bird Treaty Act. The goal of the SFBJV is to bring together public and private

agencies, conservation groups, development interests and others to protect, restore, and increase wetlands and wildlife habitat to benefit, birds, fish and other wildlife throughout the nine county SFB region. Although the SFBJV does not itself have funding for conservation management or restoration of tidal marshes, nor does it manage tidal marshes itself, it represents a collaborative partnership of many of the agencies involved in planning, acquisition, restoration and management of tidal marshes.

*The Problem (**Pr**OACT)*

Under the SDM process, our initial task was to identify and state the overarching problem we were addressing in the workshop. With climate change, many established tidal marshes and ongoing and proposed restoration projects will be affected by SLR and increased storm frequency and intensity (Cayan *et al.* 2008). Our team was interested in providing a framework for making decisions and planning for climate change impacts on SFB tidal marshes so that ecosystem functions are maintained and recovery criteria for many listed endemic wildlife species are achieved.

Primary objectives for conservation management agencies for tidal marshes in SFB are to maximize habitat quantity, connectivity and quality for endangered species or species of concern for their long-term recovery and survival. Our group determined that climate change adaptation management actions may include focusing efforts on tidal marshes with the largest populations, creating refugia within existing marshes, restoring areas with the highest accretion potential, acquiring lands with adjacent open space, or building levees with gradual slopes to allow marshes to migrate. Potential key uncertainties include the rate and extent of SLR to 2100 and the response of the tidal marshes (e.g. will accretion keep up with SLR). In addition, it is uncertain whether and when management actions would contribute to the persistence of the protected species.

We evaluated a series of questions related to SFB tidal marshes in light of climate change:

- 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 a focus be on preserving existing tidal marshes or on creating or re-establishing them?
- Should there be a focus on particular target species?

At the end of our discussion, we developed a one-sentence problem statement that best captured the concerns of the workshop participants. Our final problem statement was:

“To conserve San Francisco Bay tidal marshes in light of future climate change, what actions (management, restoration, protection) if any should be conducted (where, when, and how)?”

Objectives (PrOACT)

Within the context of our problem statement, we listed several possible objectives for the decision framework (Table 2). These objectives included both fundamental objectives which represented the ultimate desired end points of tidal marsh management, as well as means objectives which were identified as intermediate steps needed to achieve the fundamental objectives.

Objectives hierarchy.-- We categorized the list of draft objectives into “bins” to begin organizing our set of fundamental and means objectives (Table 3). These bins were a starting point for distinguishing fundamental from means objectives that addressed the problem statement. From our discussions, five fundamental objectives (*see* definitions) emerged: (1) maintaining or improving ecosystem function or services at multiple spatial scales, (2) achieving species recovery, (3) maximizing upland transition zones and diversity considering regional spatial scales and connectivity, and (4) maintaining and expanding tidal marsh extent. These conceptual objectives would form the basis for measureable attributes described under Decision Analysis.

We also used an objectives hierarchy diagram (Figure 1) to identify relationships among the suite of fundamental objectives while further distinguishing means objectives from fundamental objectives. We were able to then categorize the objectives into ecosystem processes, services, and functions as well as the human benefits of conserving tidal wetlands (Table 3B). Finally, for communication purposes, we summarized the objectives into an overarching single fundamental objective:

“To perpetuate marsh ecosystem function and services, and human benefits by maximizing resilience to climate change.”

Alternatives (PrOACT)

Alternative actions were developed through identification of management actions that could support the overarching fundamental objective. Over 20 alternative actions were identified and

discussed (Figure 2). The list of alternative actions was not considered exhaustive by the group, but an effort was made to identify a wide range of options without restricting them. For example, alternative actions discussed even included potential measures to remove the influence of SLR itself, (i.e. through installing water controls under the Golden Gate Bridge or employing a “bucket-brigade” to move water seaward). We expected that the list of potential alternative actions could be greatly expanded with more time and effort. After developing an initial list, similar alternative actions were grouped into five management strategies categories (Figure 2). These categories would be the basis for further discussion of resource allocations to alternative actions and the consequences and tradeoffs with their implementation.

Alternative management strategy categories:

Do Nothing.-- In light of climate change effects, the benefits of restoration and management actions in tidal marshes may be diminished. Thus, we considered the option of stopping all current and planned restoration projects in SFB. This was considered an extreme possible option, similar to the *no action* alternative reviewed in many environmental impact statements.

Status Quo.-- To pursue existing tidal marsh goals with nominal consideration of climate change in implementation and planning. In this case, unlike the Do Nothing option, ongoing tidal marsh restoration and actions would continue, however no activities to address climate change effects would be added. It was recognized that the term “status-quo” is not truly reflective of current practice, as many project managers in SFB have begun incorporating climate change strategies into their policy and planning processes. However, we used the term to reflect the limited consideration of climate change in previous management.

Climate Restoration.-- Restoration actions to increase the resiliency of tidal marshes to climate change effects. Potential actions included exploring engineering options to improve resilience of future or past tidal restoration efforts to SLR and storms, developing options for improving the health of existing tidal marshes, and improving our understanding (modeling) of how tidal marshes will respond to climate change.

Marsh Migration.-- Encompasses actions that would allow transgression upslope of tidal marshes with SLR. Alternatives include identifying and prioritizing areas where tidal marshes could migrate, acquiring open lands adjacent to existing tidal marsh, and removing infrastructure barriers to marsh transgression.

Wildlife Adaptation.-- Wildlife adaptation was a category of actions that could increase resiliency of wildlife species of conservation concern in response to climate change. Possible actions included translocation, captive breeding, and creation of artificial habitat elements (e.g.,

floating nest platforms).

Resource allocation among alternative actions

Next we considered the availability of resources (e.g. funding, time) for implementing alternative strategies focused on mitigating the effects of climate change. We considered that resources are finite to implement actions; therefore we examined several alternative temporal allocation sequences among strategies (Figure 3).

For the purpose of our initial prototype, we only considered variation in timing of resource allocations across the entire SFB, rather than considering the myriad of alternative allocations if we specified particular sub regions or areas. SLR is expected to rise slowly and consistently (linearly) from the present to 2050 and sharply upward (exponentially) from 2050 to 2100 (Cayan *et al.* 2009). Thus, we limited our initial prototype to allocations among alternative actions available in the near future: a short-term period from 2012 to 2020 and a longer-term period from 2020 to 2050. These time periods were based on current planning and response horizons for wetland restoration projects already in progress (short-term) and for implementation of new projects under consideration (longer-term).

We first considered a Status Quo Allocation that represented a continuation of current efforts to restore historic tidal marsh with nominal consideration of climate change in tidal restoration design (Figure 3A). Relative allocation of resources to climate restoration, marsh migration, and wildlife adaptation would remain at low levels ($\leq 15\%$) through 2050. The Marsh Migration Allocation represented increasing resources for climate restoration actions by up to 70% by 2020 (Figure 3B). At 2020, allocation to climate restoration would begin to decrease and allocation for marsh migration would steadily increase to 70% by 2050. The Climate Restoration Allocation represented an increase in resources for climate restoration to 70% by 2020 continuing through 2050 (Figure 3C). Marsh migration and wildlife adaptation would remain at low levels ($\leq 15\%$). Under the Climate Restoration + No Wildlife Allocation, resources for climate restoration would increase to 80% by 2020 and remain at that level through 2050 (Figure 3D). Resources for marsh migration would increase to 20% and remain at that level through 2050. Actions aimed at wildlife adaptation would decrease to 0% by 2015 and remain at that level through 2050.

Decision Analysis

Consequences (PrOACT)

After establishing our set of alternative actions and considering allocations, we examined how they might satisfy our overarching fundamental objective to perpetuate tidal marsh into the

future. To be able to compare our alternative allocations, we used models to predict their consequences in terms of our fundamental objectives. These models are schematic and were intended to provide guidance and insight into trade-offs and optimization across a set of alternative actions. Models also can be used to perform a sensitivity analysis to illustrate where uncertainty is the greatest and to identify where resources should be directed to obtain improved understanding.

Our first step was to build a model linking actions to our fundamental objectives (Figure 4). Here, a healthy tidal marsh is one that supports a diverse community of native marsh species. For the first prototype, the California clapper rail (*Rallus longirostris obsoletus*), was chosen as an example to examine endangered species management within the context of this ecosystem decision making framework. It also was discussed that an index for marsh ecosystem health be included as a fundamental outcome to represent elements of the ecosystem that are independent of clapper rail habitat requirements such as native plant diversity.

The next challenge was to specify measures for the fundamental objectives so that the outcomes could be modeled (Table 3). The example chosen metric was California clapper rail recovery, which was defined as the likelihood of species recovery as defined by the collective likelihood of meeting all the habitat requirements for this species as defined in the tidal marsh recovery plan (USFWS 2009). Expected outcomes for marsh ecosystem health and human benefit were each defined as multi-metric indices composed of multiple parameters. Marsh ecosystem health was based on the acreages of marsh within three elevation classes (i.e., low, mid, and high), and native plant species richness, and accretion rate (Table 3). This marsh ecosystem index ranges from 0-5, which is the sum of scores for the five individual ecosystem components. Each ecosystem component would receive a score of 0-1, with 1 being the most desired and 0 being the least desired outcome. For example, no native plant species would receive a score of zero, whereas 10 native plant species would receive a score of 1. The human-benefits index is based on the expected incidences of mosquito-borne diseases, loss of infrastructures due to flooding, and recreational opportunities. As with the ecosystem index, each component would receive a score of 0-1 then summed for a total human-benefit score of 0-3.

Two management response time horizons were used, the year 2020 and 2050. These dates were chosen because 2020 was considered a common planning horizon and the implementation timeline for ongoing restoration projects. The year 2050 was chosen to coincide with the timeframe within which the trajectory of SLR is most confident; SLR uncertainty increases greatly beyond mid-century.

External influences included in the first prototype were extreme storm events and a fixed-budget available for alternative allocations through 2020 (Figure 6). Extreme events were defined by the

number of storm events occurring per year, either from 0-1 or 2-5. The San Francisco Bay restoration budget through 2020 was estimated from low values of \$60-\$299 million to high values of \$300-\$400 million dollars. The 2021-2050 budget was modeled as being affected by the 2020 human benefit, which in turn affected the marsh ecosystem health in 2050.

We developed our decision-analytic prototype by employing a decision support tool, a Bayesian Belief Network (BBN) using Netica (Norsys Software Corp; Vancouver, BC, Canada: (<http://www.norsys.com/>) a freeware program. BBNs allow for graphical representation and analysis of probabilistic relationships among a set of random variables (Pearl 1988). A BBN provides a platform to identify an optimal decision to maximize a utility value while accounting for uncertainty about management effectiveness and environmental dynamics. The utility value is ultimately determined by the decision maker(s) and can integrate multiple objectives allowing an explicit consideration of tradeoffs for complicated problems. A utility function within Netica allowed us to quantify how the decision maker values potential outcomes for alternative allocations. This was done in terms of our fundamental objectives, including a Marsh Ecosystem Function index for 2020 & 2050, Human Benefits index for 2020, and Clapper Rail recovery status for 2020 & 2050. An influence diagram was developed (Figure 4) and measurable fundamental objectives were summarized as indices (Table 3). We used a Delphi method (Linstone and Turoff 1976) to elicit expert opinions from team members when quantifying utilities and relationships in the BBN indices. These relationships included budget amounts and extreme storm events expressed as probabilities (0-100%) within the Netica framework (Figure 6). SLR was treated as a constant value in this prototype due to the shorter time horizon, because SLR is expected to have a gradual linear increase through 2050 (Cayan *et al.* 2009).

The BBN allowed us to evaluate how well our alternative action strategies met our fundamental objectives. The component relationships linking decisions to fundamental objectives accounted for probabilistic effects of our alternative strategies and other external factors. To determine the utility, each participant evaluated the possible 32 combinations of outcomes and independently ranked their utility (Table 4). Each participant also predicted the consequences for our fundamental objectives when doing nothing or conducting one of the four alternative allocations (Figure 3) while accounting for uncertainty about storm severity (high or low; Figure 6). Experts assessed external factors (storm events, and low and high budget scenarios for the periods of 2011-2020 and 2021-2050) with regard to their influence on tidal marsh indices, human benefits and California clapper rail recovery. Arrows indicate directions of relationships and the utility function indicates the best solution.

Tradeoffs and optimization (PrOACT)

As with parameterizing predicted outcomes in our BBN, team members were also asked to first independently assign their utility values to alternative possible outcomes in terms of the fundamental objectives. There were differences among individuals in how they assigned these utility values. For example, some members valued short-term (through 2020) benefits more so than long-term (through 2050) benefits and vice-versa. Likewise, the utility value placed on successful California clapper rail recovery relative to the Marsh Ecosystem Index (see Table 3) varied among participants, which represented a broad set of resource managers, funders, and regulators in SFB. To build a collective utility function for each possible outcome, all individual rankings were combined across team members to calculate an average value. Before accepting the combined rankings, the group examined the average and range of values for each of the 32 combinations to determine a consensus number. We could have weighed the relative importance of each expert's input according to their level of background but in this case, the team decided to weight each individual's contribution equally.

To identify an optimal decision, the group asked after examining the initial BBN results “*What gives us the highest utility given the relevant uncertainties?*” The optimal decision identified in this manner was the Climate Restoration Allocation (Figure 5). We then tested the sensitivity of the model by exploring the impacts of the considered factors on utility by fixing certainty about individual parameters. For example, assuming that likelihood of California clapper rail recovery was 100% (all recovery goals have been met) at both time horizons (2020 and 2050), we found that while absolute utility values varied, the relative utility among alternatives themselves and the optimal decision remained unchanged (Figure 6). Based on our findings, allocations to address climate change effects were more beneficial than the Do Nothing or Status Quo allocations while accounting for uncertainty about model parameters. The Climate Restoration Allocation provided the most beneficial results despite uncertainty about considered socioecological factors. In particular we found that the optimality of the Climate Restoration Allocation was robust to uncertainty about the Marsh Ecosystem Index at 2020 and 2050, Human Benefits by 2020, and the available budget at 2020 and 2050 (Figures 6-9). One notable exception was that the Climate Restoration Alternative only became suboptimal under a very pessimistic scenario when it was assumed that California clapper rails would not be recovered and that the marsh ecosystem would have a low-health index over both response horizons (Figure 10). Under this very pessimistic and definite scenario, however, the utilities of the alternative allocations were all very low and nearly identical, indicating that collecting additional information to resolve uncertainty about model parameters may not be worthwhile in practice.

We also examined the consequences of applying specific alternative allocations (Figures 3, 11). The Climate Restoration + No Wildlife Allocation had a lower predicted likelihood of California clapper rail recovery by 2020, compared to the Climate Restoration Allocation which contained wildlife adaptation management actions (Figure 11). Despite their initial similarities up to 2020,

the Climate Restoration Allocation has a slightly greater predicted benefit for Marsh Ecosystem function in 2050 than did the Marsh Migration Allocation or the Climate Restoration + No Wildlife Allocation. We would have expected the marsh ecosystem index to have a higher predicted level under the Climate Restoration + No Wildlife Allocation compared to the Climate Restoration Allocation where fewer resources are dedicated toward marsh restoration and more instead toward wildlife adaptation management actions. As minimal resources (if any) were allocated to wildlife management actions in our allocation scenarios compared to other efforts, allocation to this set of management actions likely had little intended influence on participants' predictions. The consequences of Do Nothing or the Status Quo Allocation on our fundamental objectives stood out as favoring no recovery and low ecosystem function, indicating both of these as unacceptable strategies in comparison to other alternative actions.

The structure and inputs of our BBN, including the predicted parameter values and utility values, were based on the collective opinion of our team members. Specifically, the predicted outcomes were based on expert opinion or best professional judgment, and the utility value for each outcome was based on the values of each expert's personal belief or organizational missions. Thus, it is possible to influence the results through the selection of the experts and stakeholders. However, greater representation of knowledge and relevant participants in the development and parameterization of the decision framework will result in a more accepted and implemented strategy.

In summary, the Status Quo Allocation and Do Nothing produced the lowest utility values throughout the sensitivity analysis. Whereas the Climate Restoration Allocation provided the largest utility under full uncertainty about parameter values in the model (50.2), followed closely by the Marsh Migration Allocation (43.9). However, the group believed that the Marsh Migration Allocation may provide larger utility to meeting objectives after 2050, when SLR is expected to accelerate.

Uncertainty

Climate change

Climate change effects to coastal ecosystems, human communities, and local economies are certain to occur. SLR rates to 2050 appear to be lower uncertainty (Cayan *et al.* 2009), however SLR rates between 2050 and 2100 are highly uncertain as they depend on CO₂ loading rates of the atmosphere, which results in differing rates of land ice sheet melting and thermal expansion rates (IPCC 2007). SLR and other climate impacts become quite uncertain in the latter half of this century but are projected to increase exponentially at some rate (Cayan *et al.* 2009, Jevrejeva *et al.* 2012). In addition, SLR models are often constructed at global and continental scales, whereas management and restoration activities are done at the local or subembayment scale.

This makes it difficult to interpolate local climate change impacts. Other climate change impacts on SFB such as extreme storm events, salinity changes, ambient and water temperature increase, and acidification are difficult to assess. Uncertainty about the rate and scale of tidal marsh impacts due to SLR and storms were considered key knowledge gaps in this effort. The results of our sensitivity analysis, however, demonstrate that resource allocation towards climate restoration actions over the next two decades may be robust to uncertainty for storm severity through 2050.

Ecosystem response

Identifying key knowledge and information gaps is important to plan effective action for maintaining marsh ecosystem integrity. In order to plan, achieve, and maintain a functioning “healthy” marsh in the face of climate change, we need to first understand underlying marsh processes and species response to management actions and climate change. These underlying physical processes (eg. accretion capability, hydrodynamics, local sediment budgets) are not fully understood for many areas and inhibit the ability to model them. In addition, modeling efforts, such as those presented here, require refinement of a measurable index that relies on the understanding of these marsh functions and responses. In this workshop we proposed a Marsh Ecosystem Index comprised of measurable attributes such as marsh area, species richness, and accretion capacity (Table 3). As this is a rather complex multi-metric index generated rapidly during the workshop, a more concerted effort is needed to construct an index that best reflects marsh ecosystem integrity in the eyes of marsh ecologists and conservationists. Ideally, each component of the index should be readily measured in the field for validating and supporting the model predictions. . As with storm severity, however, the results of our sensitivity analysis indicate that optimality of the Climate Restoration Allocation over the next two decades may be robust to uncertainty about marsh ecosystem response.

Wildlife species response

We identified wildlife species responses to local changes in SLR and extreme storm events as a key uncertainty. While important wildlife species requirements for food, reproduction, cover, and breeding in current conditions are generally understood, conservation or restoration needs of these key attributes would be difficult to identify. In addition, the level of understanding of the combined response of tidal marsh wildlife to existing stressors (e.g. predation, pollution) with new climate change stressors is low. As with other environmental parameters, the results of our sensitivity analysis indicate that optimality of the Climate Restoration Allocation over the next two decades may be robust to uncertainty about California clapper rail recovery.

Societal and political support

Reducing existing stresses (e.g. urbanization, fragmentation, pollution) on tidal marsh ecosystems and resident wildlife can be one of the most effective and feasible ways to increase resiliency to climate change. Over the past decade, there have been increasing calls for action by government and non-governmental entities to better understand and address the impacts of climate change on natural resources and the communities that depend on them, yet it is uncertain if public support will allow these programs to continue. This is especially important when considering how to continue to restore and manage tidal marsh ecosystems in this uncertain future and the likely substantial costs. While we have a rough understanding of the available budget for tidal marsh restoration through 2020, budget needs will become less certain through the years. This is further complicated by the uncertainty and difficulty in effectively estimating costs of yet unknown climate restoration and management options. Adaptation efforts will be most successful if they have broad public and political support which can motivate management agencies to take action. As with other parameters in the model, the results of our sensitivity analysis indicate that optimality of the Climate Restoration Allocation over the next two decades may be robust to uncertainty about budgets and projected human benefit.

Discussion

Value of decision structuring

This is the first attempt to use a SDM framework to examine the problem of managing and restoring tidal marshes in SFB with climate change. SDM is an organized approach to identifying and evaluating complicated problems and making choices in complex decision structures. This process delivers insight for decision makers about their objectives and how they may be satisfied by alternative actions. The process helps build consensus by identifying perceptions of trade-offs that may exist between alternative actions. This method is very helpful for facilitating multi-disciplinary problems and stakeholder involvement.

Many agencies are struggling with the problem of climate change adaptation for tidal marshes and the associated uncertainties. The SDM approach allowed us to consider this uncertainty explicitly while having key SFB partners work together to discuss their shared issues in devising a collaborative decision framework. By attempting to identify the full host of variables to be considered, the decision process becomes more transparent aiding in efficiency for future efforts. This transparency also aids in policy development, which often translates to funding decisions and helps illustrate how thoroughly the topic was evaluated or not.

The outcome of this workshop was not a final result, but instead a first prototype to address this complex problem. We hope to continue developing the prototype by eliciting other expert opinions and continuing to define the problem statement, as well as identifying information gaps and science needs. Subsequent prototypes coupled with more thorough testing of the assumptions will lead to results that may effectively drive decision making in SFB. We hope this will result in a prototype that can be revisited within a decision framework as perceptions and knowledge changes. Ultimately, the decisions on which actions to take are linked, and we established a decision framework for addressing those linkages and assumptions.

Conclusions

Under the SDM process, we developed an initial prototype. After discussion we were able to reach broad agreement on the problem statement: *“What actions (management, restoration, protection) if any should be conducted (where, when, and how) to conserve SFB tidal marshes in light of future climate change?”* We were able to group multiple fundamental objectives for addressing the problem under a single fundamental objective *“to perpetuate marsh ecosystem function and services, and human benefits by maximizing resilience to climate change.”*

Over 20 alternative actions were generated by the group to achieve the fundamental objective, from those we developed five management action categories ranging from Do Nothing (cease funding for tidal marsh management and restoration), Status Quo (continue current management without climate change adaptation), Climate Restoration (adapt current and proposed tidal marsh restoration for climate change), Marsh Migration (manage areas for upslope transgression), and Wildlife Adaptation (build wildlife resiliency to climate change with habitat elements, captive propagation and translocation).

We used a BBN and expert elicitation from the team to identify the expected consequences and tradeoffs of these actions in maximizing tidal marsh health while conserving endangered species, here represented by the California clapper rail. Our results indicated that the Climate Restoration Allocation is optimal across a range of uncertainty about identified socioecological factors when managing tidal marshes. The Marsh Migration Allocation also provided high utility in this management context. The Status Quo Allocation provided half the relative model utility value of those two options, while Do Nothing provided a quarter of the utility value. There was a large difference between prediction and utility values among individual team members that were averaged for the analysis (Tables 5-6). An increased effort to improve knowledge and elicit additional experts about tidal marsh dynamics could reduce the range of prediction and utility values among participants. A sensitivity analysis at the level of individual experts has yet to be conducted.

Future Development

We hope to refine this prototype to address questions and identify management alternatives with the highest utility considering the many sources of uncertainty. This prototype only evaluated a single protected species; therefore future iterations should address the tradeoffs of alternative actions among protected species. In future prototypes of this decision framework, additional SLR and planning timeframes (eg. 2050-2100) and more refined spatial resolution will need to be included. In addition, the inclusion of additional topical working group experts that can increase the level of knowledge for refining our decision framework will be needed to better account for uncertainty about ecosystem responses and SLR. Developing a decision framework that provides an optimal annual sequence of allocations, rather than choosing among a limited set of alternative allocations should be implemented in future prototypes. Continued development of this approach may occur within the construct of the San Francisco Bay Joint Venture and ongoing work of the California Coastal Conservancy in the Bayland Ecosystem Habitat Goals Project.

Recommendations

Based upon this initial attempt to utilize SDM to address the complicated issues related to climate change in SFB, our analysis indicates that climate restoration actions or possibly efforts to aid marsh migration should be considered. This initial analysis did not attempt to identify geographic areas for focused restoration or mitigation efforts, but only addresses SFB-wide needs. Future applications of this decision framework should incorporate analyses of different geographic areas of the SFB estuary. Our results suggested that status quo and doing nothing provided the least utility for our fundamental objective. Climate restoration as we have defined it here includes no efforts to provide species-specific management actions. Examples of species-specific management actions could include earthen island construction, floating habitat island and targeted re-vegetation efforts to provide high water refugia from storms and SLR. In addition, species translocation and captive breeding of imperiled species (e.g., federally listed species) could be viewed as management actions.

For continuing development of the SDM process and the BBS modeling, we suggest a few directions:

- Continue refining the decision framework for this problem through the San Francisco Bay Joint Venture and Baylands Goals Project of the State Coastal Conservancy through meetings with an expanded pool of experts and decision-makers
- Broaden expert elicitation and rerun models with additional target species or other key parameters
- Include smaller spatial areas (embayments or sub-regional shoreline areas) in future analyses

- Include the period from 2050 to 2100 when SLR accelerates with increased uncertainty and marsh migration may increase in importance.
- Construct and evaluate additional alternative allocations focused on climate restoration and marsh migration
- Consider the linked consequences with other habitat types (mud flat, upland) and associated species

Definitions

Actions – steps taken to achieve stated objectives

Allocations – proportional expenditures among alternative management actions, which may be specified for a single implementation or a series of implementations over time.

Bayesian Belief Network (BBN) – a belief network or probabilistic graphical model that encodes probabilistic relationships among things of interest.

BCDC – San Francisco Bay Conservation and Development Commission

CALCC – California Landscape Conservation Cooperative

CDFG – California Department of Fish and Game

Climate restoration actions — changes to current or planned projects in tidal marshes to increase resiliency of the areas to sea-level rise effects.

Climate Restoration Allocation — represents a dramatic increase in resources toward climate restoration actions and a modest increase in marsh migration actions across the next decade.

Climate Restoration + No Wildlife Allocation -- represents a dramatic increase in resource allocation toward climate restoration, a modest increase in marsh migration, and elimination of status quo and wildlife allocations by 2020.

Consequences – predicted outcomes produced by actions. These can be represented by models that link actions to outcomes reflecting the fundamental objectives. Models can provide guidance for selecting a management alternative through optimization. Tools for optimization include, but are not limited to, consequence tables, decision trees, and search algorithms.

Decision maker – person or group that is responsible for policy and practices to be implemented. The decision maker may consider input from multiple stakeholders, such as state, county, city, and federal agencies.

Do Nothing -- stopping all current and planned restoration projects.

Extreme events – are significant determinants from the norm, usually described as heat waves, storms, floods, and droughts.

Fundamental objective – the most basic value and overarching ends that are trying to be achieved by the group.

Knowledge objective – a goal to better understand SLR effects through research and modeling

Linked decisions – important decision problems require the selection among alternatives that greatly influence decisions in the future. Such decisions are a series of dependent or connected decisions, meaning that choices about what to do now need to consider other future decisions.

Marsh migration actions -- provide opportunities for tidal marshes to expand upslope to uplands or into undeveloped areas with SLR

Marsh Migration Allocation -- represents a dramatic increase in resources toward climate restoration actions in the next decade and subsequent decreased effort through 2050. With decreased allocation to status quo and climate restoration actions beyond 2020, increased allocation is dedicated to marsh migration actions from 2020 to 2050.

Means objectives –ways of achieving fundamental objectives, which can lead to alternatives

Models – a way to represent logic to make predictions of outcomes and consequences

Netica – is a freely available computer program for developing and analyzing Bayesian Belief Networks that are formal, quantitative representations of networks and influence diagrams used for identifying optimal management decisions in the face of uncertainty

NPS – National Park Service

Objectives – what the group strives to achieve using an explicit statement that should capture implied trade-offs and be value based.

Objectives hierarchy – a list of objectives brainstormed which are used to develop the final fundamental objective and then sub objectives. Objectives -> measurable attributes -> performance criteria

Optimization – identifying the management alternative providing the most desired outcome (i.e., maximum utility) among a set or range of management alternatives, which usually involves quantitative decision analysis.

Perpetuate – to maintain or increase the current amount of tidal marshes in San Francisco Bay

PrOACT – an acronym for the five steps from Smart Choices. Pr=Problem, O=objectives, A=alternatives, C=consequences, T=tradeoffs (Hammond *et al.* 1999).

Process objective – a goal that improves the planning process for reaching decisions

Recovered – listed species that has met its criteria for no longer being endangered or threatened defined by the U.S. Fish & Wildlife Service, and CA Fish & Game

Resilience -- the capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly

Sea-level rise (SLR) – rise in the level of the surface elevation of the ocean. Model predictions summarized by the California Climate Change Action Team (Cayan *et al.* 2009) indicate that SLR will increase gradually between now and 2050 and more rapidly and uncertainly after 2050 due to CO₂ loading of the atmosphere.

Sensitivity analysis – examine how the optimal decision and the expected outcome is affected by uncertainty about system dynamics and management effectiveness.

SFBJV – San Francisco Bay Joint Venture

Status quo -- pursue existing tidal marsh goals with nominal consideration of climate change in implementation and planning.

Status Quo Allocation -- represents the current management allocation for climate change adaptation in San Francisco Bay held constant from 2010 to 2050.

Structured Decision Making (SDM) – a process and organized analysis of a problem in order to reach decisions that are focused clearly toward fundamental objectives. It is based in decision theory and risk analysis.

Tradeoffs –weighting among multiple fundamental objectives

Upland Transition – open space where marsh transgression is possible upslope

USACE – United States Army Core of Engineers

Utility –quantified value a manager places on a possible outcome in terms of a fundamental objective or set of fundamental objectives, which may be maximized in a quantitative decision analysis.

Wildlife adaptation actions – a suite of management methods such as captive breeding, translocation, and nesting structures that enhance endangered species population survival or numbers

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Tables and Figures

Table 1. Invited participants and members of the Structured Decision Making (SDM) workshop on climate change and tidal marsh restoration in San Francisco Bay.

Participants	Agency	Position
Valary Bloom	USFWS Region 8 Recovery Branch	recovery biologist
Giselle Block	USFWS Region 8 Inventory and Monitoring	I & M biologist
Debby Crouse	USFWS Endangered Species Office	endangered species, SDM asst. coach
Jonathan Cummings	University of Vermont	PhD candidate, SDM intern coach
Matt Gerhart	California State Coastal Conservancy	climate change manager
Steve Goldbeck	Bay Cons. & Development Comm.	chief deputy director, climate change
Nadine Hitchcock	California State Coastal Conservancy	deputy director
Beth Huning	SFB Joint Venture	JV coordinator
Jamie O'Halloran	US Army Corps of Engineers	environmental planner
Brady Mattsson	USGS Western Ecological Research Center	research biologist, SDM coach
Christina Sloop	San Francisco Bay Joint Venture	science coordinator
Mendel Stewart	USFWS San Francisco Bay Nat. Wildl. Ref.	project leader
John Takekawa	USGS Western Ecological Research Center	research wildlife biologist, SDM coord.
Karen Taylor	California Department of Fish and Game	area biologist
Karen Thorne	USGS Western Ecological Research Center	climate change biologist, SDM asst. coord.
Laura Valoppi	USGS Western Ecological Research Center	South Bay salt ponds lead scientist

Table 2. Draft objectives to address the problem statement.

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 3A. Measureable components of fundamental objectives considered for tidal marsh management in San Francisco Bay. The components used for the analysis are marked with an asterisk (*). A primary goal was to support California Clapper Rail recovery which represented the many listed species in tidal marshes of San Francisco Bay, and all habitat criteria would need to be met before the species could be considered recovered. Human benefits were included to represent the value to society of the adaptation actions. Whereas, marsh ecosystem integrity represented the intrinsic value of tidal systems.

Metrics for fundamental objectives		
California Clapper Rail Recovery*	Marsh Ecosystem Index	Human Benefit
Channel complexity	Elevation (high/mid/low)*	Human health (i.e., mosquito-borne disease)*
Invasive species density	Connectivity	Carbon sequestration
Connectivity of marsh	Size (hectares)*	Recreation (hiking, fishing, hunting, boating, bird-watching)*
Size of marsh	Native plant species distribution	Property values
Shape of marsh	Native plant species occupancy	Education
Predation rates	Native plant species richness (#/area)*	Human safety (i.e., loss of infrastructure)*
Adult and young mortality rates	Contaminant levels	
Elevation (low marsh)	Salinity levels	
Containment levels	Water quality parameters (eg. pH, DO)	
Abundance	Upland edge condition, acres, shape	
Distribution	Sediment properties (concentration, deposition rate, accretion rate*) Primary productivity	

Table 3B. Classifications of objectives (column headings) for tidal marsh management in San Francisco Bay.

Ecosystem Processes	Ecosystem Functions	Ecosystem Services	Human Benefits
Maintenance of marsh elevations	Refugia	Flood mitigation	Recreation, angling, swimming
Ability to buffer extreme events	Diversity	Carbon sequestration	Homes, property values
Marsh migration	Nesting and foraging	Water quality	Commercial fisheries
Sediment dynamics	Primary production	Reduce erosion	Support economy
	Nursing/spawning habitat	Shoreline stabilization	Aesthetics
	Aquatic food web		

Table 4. Netica table showing a subset of utility values for each combination of temporally explicit outcomes in terms of the fundamental objectives . The Utility values were elicited from the team members.

Node: **Utility** Apply Okay

Deterministic Function Reset Close

Marsh_Ecosyst_Index2020	Human_Benefit_2020	Clapper_Rail2050	CLRA_2020	Marsh_ecosystem_Index2050	Utility
Low0 3	Low	Unrecovered	Unrecovered	Low0 3	0
Low0 3	Low	Unrecovered	Unrecovered	High4 5	23
Low0 3	Low	Unrecovered	Recovered	Low0 3	19
Low0 3	Low	Unrecovered	Recovered	High4 5	32
Low0 3	Low	Recovered	Unrecovered	Low0 3	29
Low0 3	Low	Recovered	Unrecovered	High4 5	43
Low0 3	Low	Recovered	Recovered	Low0 3	44
Low0 3	Low	Recovered	Recovered	High4 5	51
Low0 3	High	Unrecovered	Unrecovered	Low0 3	16
Low0 3	High	Unrecovered	Unrecovered	High4 5	41
Low0 3	High	Unrecovered	Recovered	Low0 3	30
Low0 3	High	Unrecovered	Recovered	High4 5	55
Low0 3	High	Recovered	Unrecovered	Low0 3	37
Low0 3	High	Recovered	Unrecovered	High4 5	64
Low0 3	High	Recovered	Recovered	Low0 3	47
Low0 3	High	Recovered	Recovered	High4 5	74
High4 5	Low	Unrecovered	Unrecovered	Low0 3	15
High4 5	Low	Unrecovered	Unrecovered	High4 5	41
High4 5	Low	Unrecovered	Recovered	Low0 3	25
High4 5	Low	Unrecovered	Recovered	High4 5	51
High4 5	Low	Recovered	Unrecovered	Low0 3	35
High4 5	Low	Recovered	Unrecovered	High4 5	60

Table 5. Netica table showing a subset of predictions for the 2050 across alternative scenarios for socioecological conditions. Predictions were elicited from the workshop team members.

Node: **Marsh_ecosystem_Inde** Apply Okay

Chance % Probability Reset Close

Marsh_Ecosyst_Index2020	Budget_2021_2050	Extreme_storm_events2011_2050	Alternative_Action_Strategies	Low0 3	High4 5
Low0 3	Low300M 700M	Storms0 1	Status Quo	76	24
Low0 3	Low300M 700M	Storms0 1	Marsh Migration	53	47
Low0 3	Low300M 700M	Storms0 1	ClimRestor	54	46
Low0 3	Low300M 700M	Storms0 1	ClimRestor NoWildlife	59	41
Low0 3	Low300M 700M	Storms0 1	Do nothing	95	5
Low0 3	Low300M 700M	Storms2 5	Status Quo	81	19
Low0 3	Low300M 700M	Storms2 5	Marsh Migration	63	37
Low0 3	Low300M 700M	Storms2 5	ClimRestor	67	33
Low0 3	Low300M 700M	Storms2 5	ClimRestor NoWildlife	72	28
Low0 3	Low300M 700M	Storms2 5	Do nothing	97	3
Low0 3	High800M 1B	Storms0 1	Status Quo	65	35
Low0 3	High800M 1B	Storms0 1	Marsh Migration	37	63
Low0 3	High800M 1B	Storms0 1	ClimRestor	39	61
Low0 3	High800M 1B	Storms0 1	ClimRestor NoWildlife	48	52
Low0 3	High800M 1B	Storms0 1	Do nothing	91	9
Low0 3	High800M 1B	Storms2 5	Status Quo	75	25
Low0 3	High800M 1B	Storms2 5	Marsh Migration	46	54
Low0 3	High800M 1B	Storms2 5	ClimRestor	51	49
Low0 3	High800M 1B	Storms2 5	ClimRestor NoWildlife	58	42
Low0 3	High800M 1B	Storms2 5	Do nothing	95	5
High4 5	Low300M 700M	Storms0 1	Status Quo	58	42
High4 5	Low300M 700M	Storms0 1	Marsh Migration	39	61

Figure 2. Potential alternative actions and broader action categories to adapt tidal marsh management and restoration for climate change effects in San Francisco Bay.

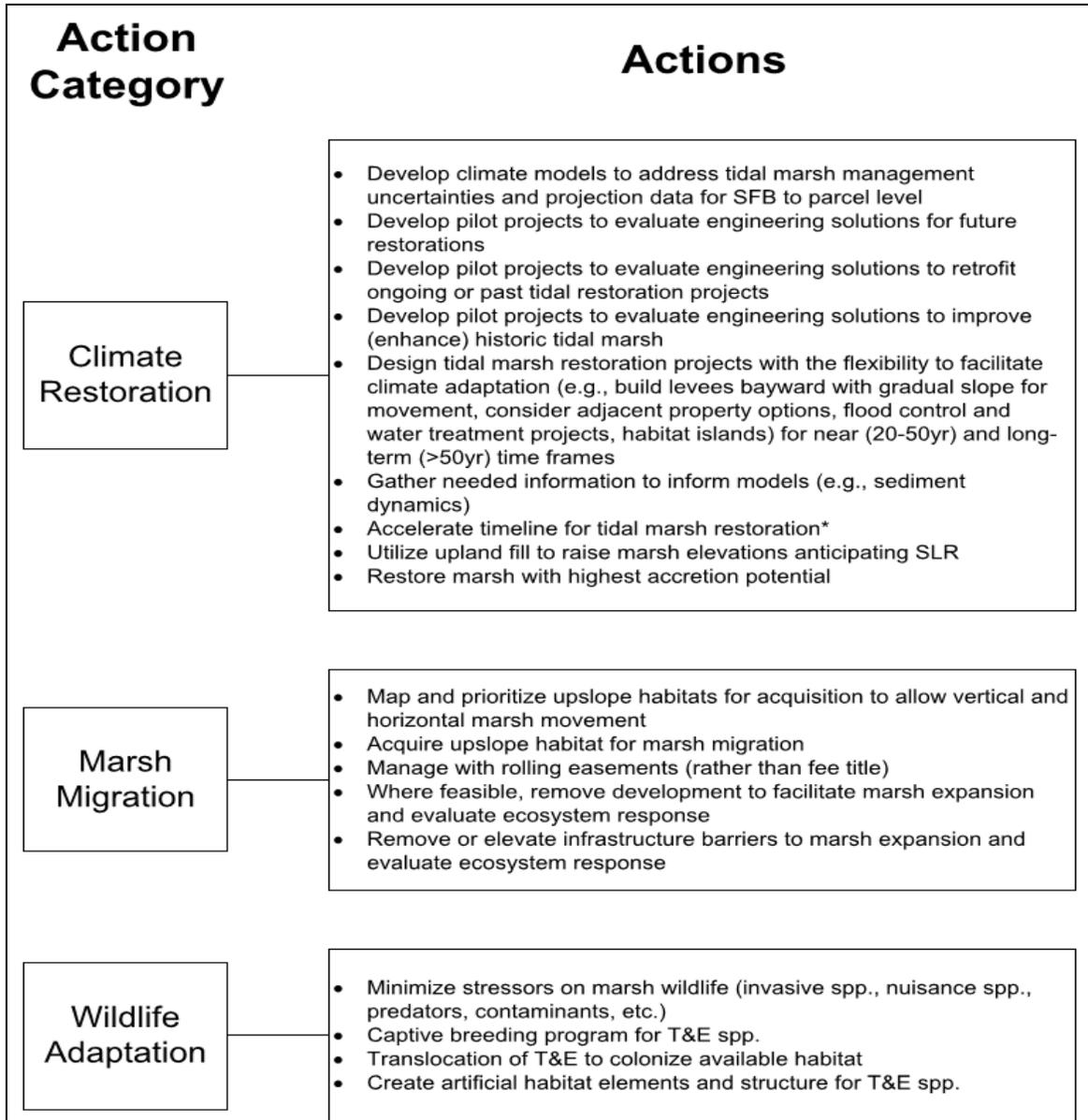


Figure 3C. Climate Restoration Allocation represents a dramatic increase in resources toward climate restoration actions and a modest increase in marsh migration actions across the next decade.

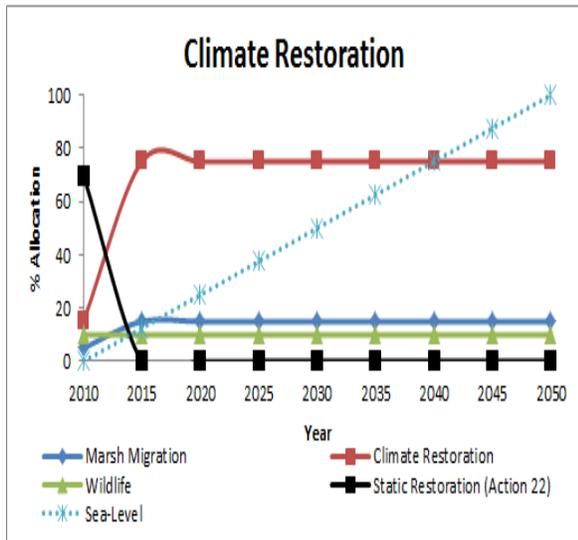


Figure 3D. Climate Restoration + No Wildlife Allocation represents a dramatic increase in resource allocation toward climate restoration, a modest increase in marsh migration, and elimination of status quo and wildlife allocations by 2020.

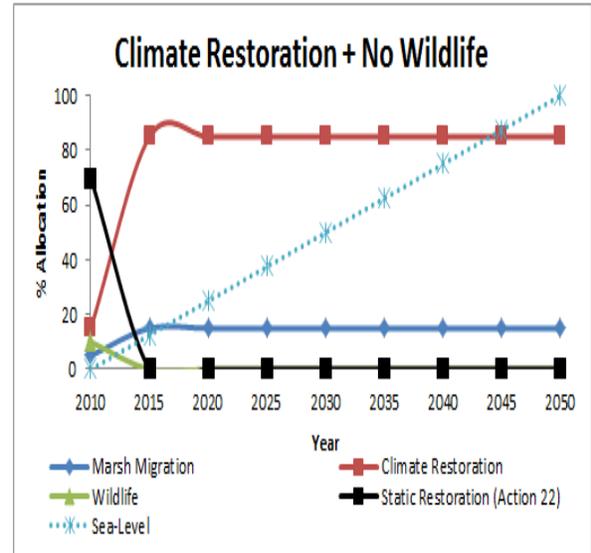


Figure 4. Influence diagram for initial prototype showing linkages among tidal marsh management actions and fundamental objectives (bold boxes), including marsh ecosystem integrity, California clapper rail recovery, and human benefits. Climatic conditions were included as an external driver of the system.

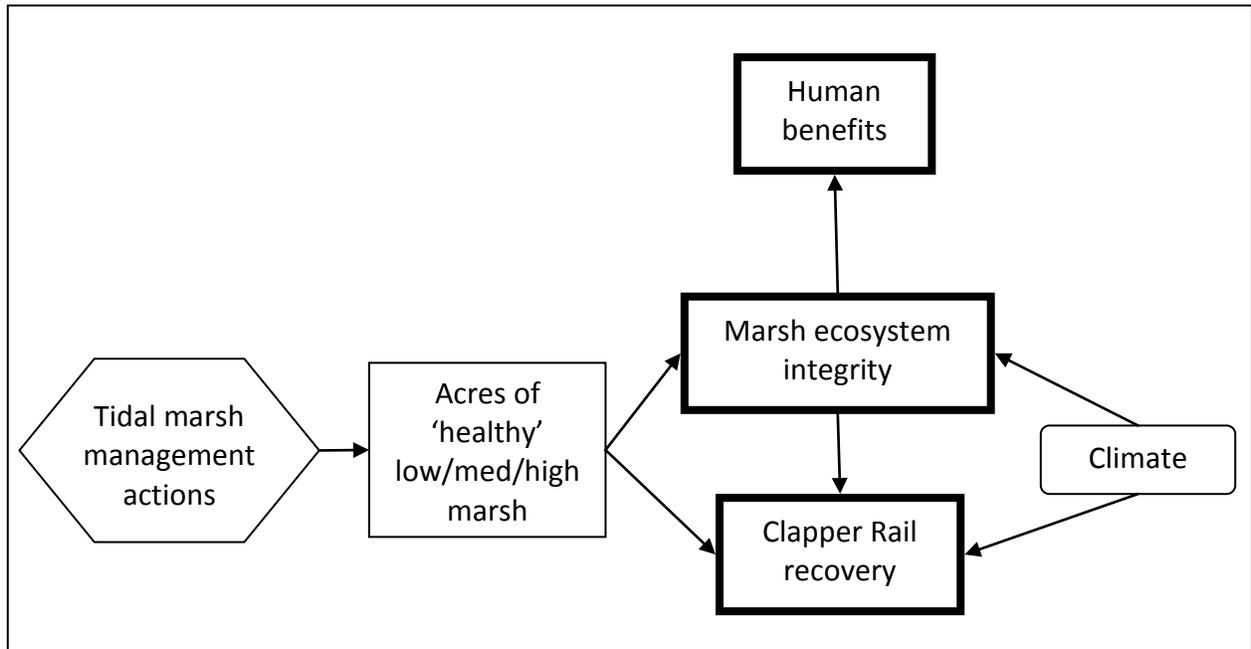


Figure 5. Bayesian Belief Network showing the optimal outcomes and expected utilities of alternative management allocations. See text for detailed explanation of the parameters within the model.

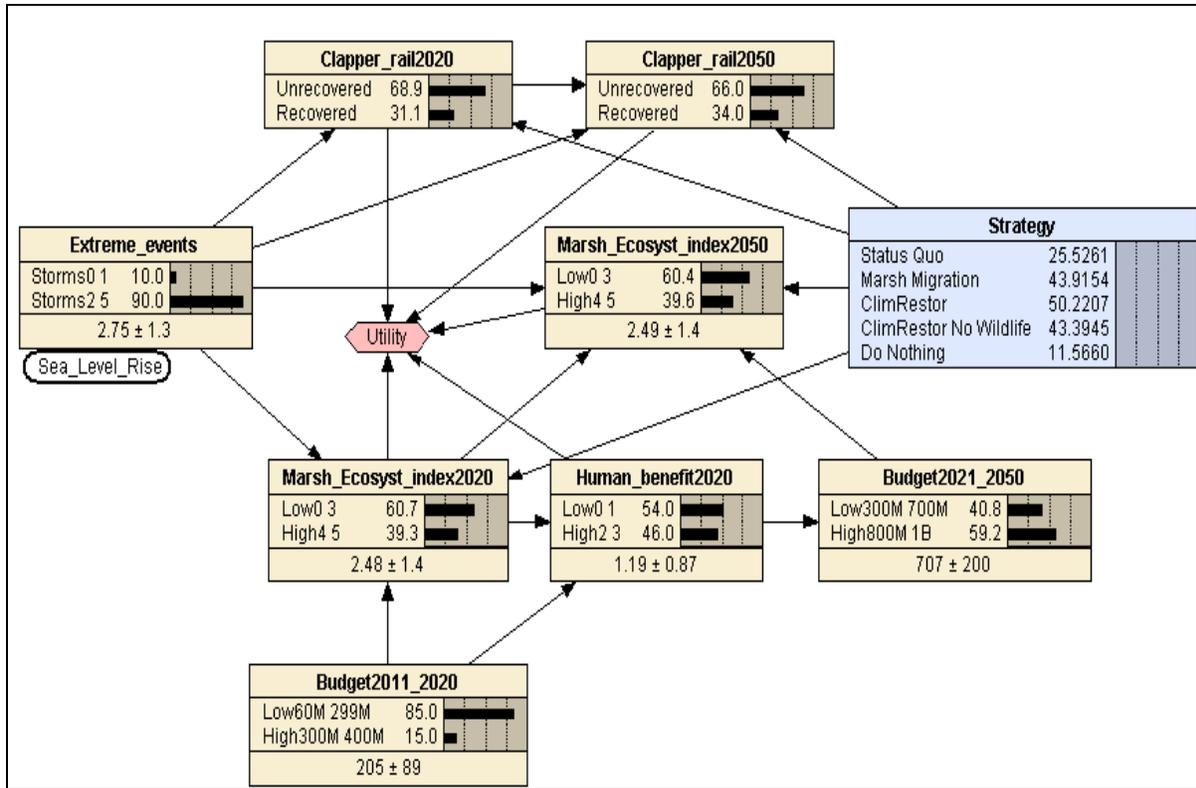


Figure 6. Bayes Net outcome diagram when uncertainty about one fundamental objective (Clapper Rail Recovery in 2020 and 2050) is removed. Our assumption in this model was that the probability of Clapper Rail recovery would be 0% in 2020 or 2050 (unrecovered = 100%). Marsh Migration (28.5) and Climate Restoration (30.1) allocations had similar utility values.

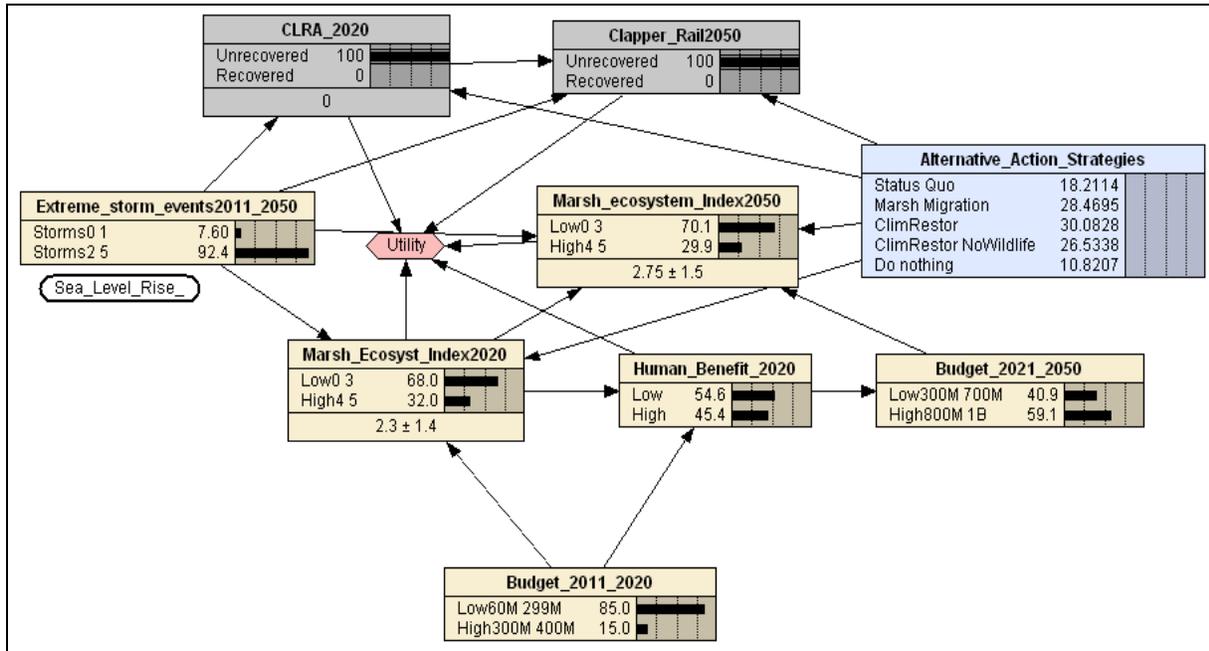


Figure 7. Bayes Net outcome diagram when the Marsh Ecosystem Index 2020 and 2050 was set to 100% chance of low recovery. Low utility values resulted for a number of allocations, but Climate Restoration Allocation had the highest expected utility (28.8).

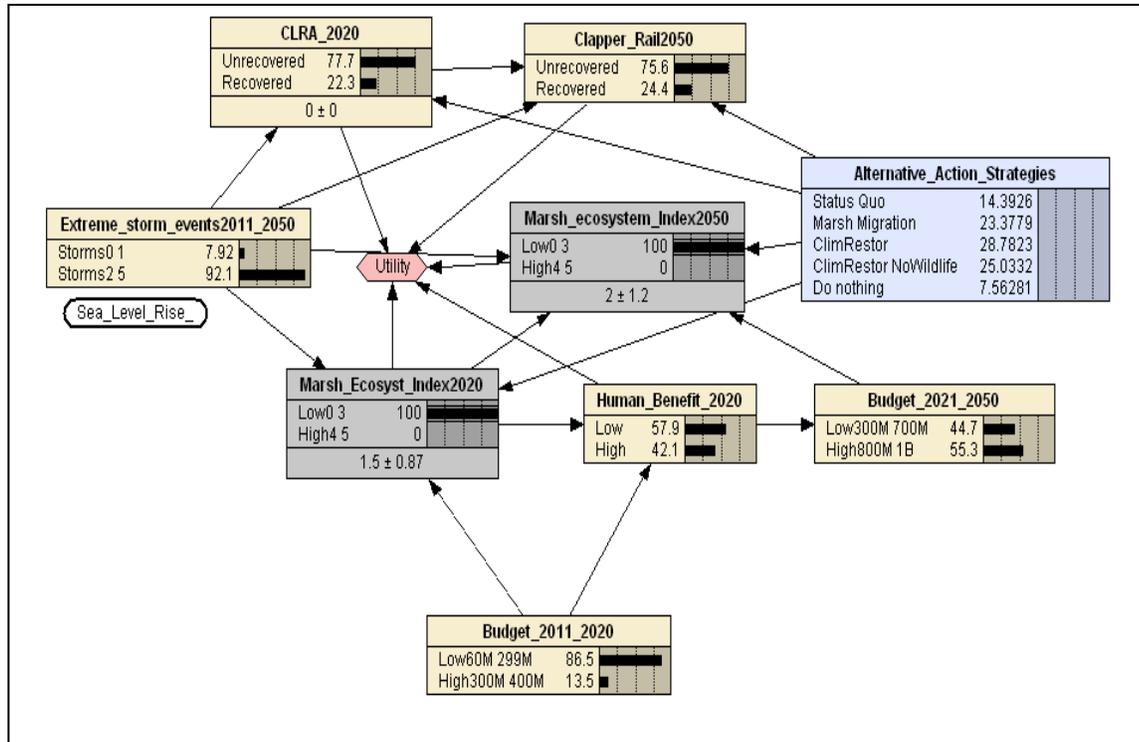


Figure 8. Bayes Net outcome diagram when Human Benefits was set to low recovery for 2020 and 2050. The Climate Restoration Allocation provided the highest expected utility (40.5).

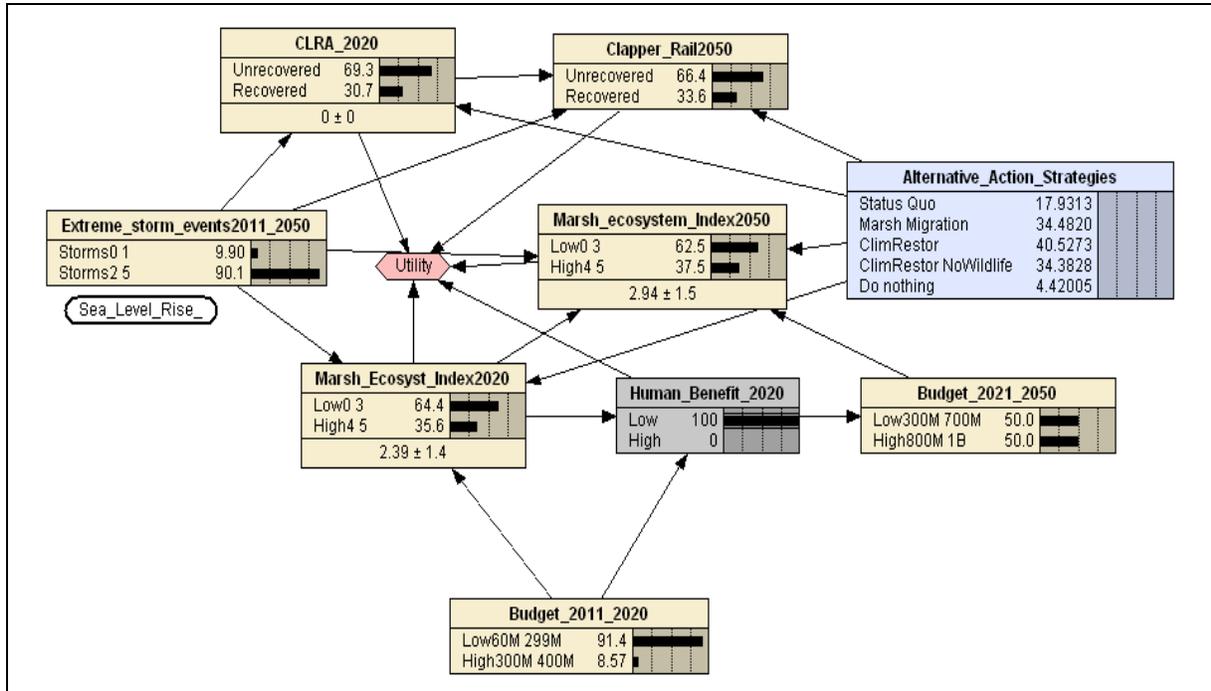


Figure 9. Bayes Net outcome diagram of the effect of removing budget uncertainty (100% low budgets for 2020 and 2050) on the expected utilities of alternative allocations. The Climate Restoration Allocation (44.6) exceeded both Marsh Migration (38.0) and Climate Restoration + No Wildlife Allocations (38.1).

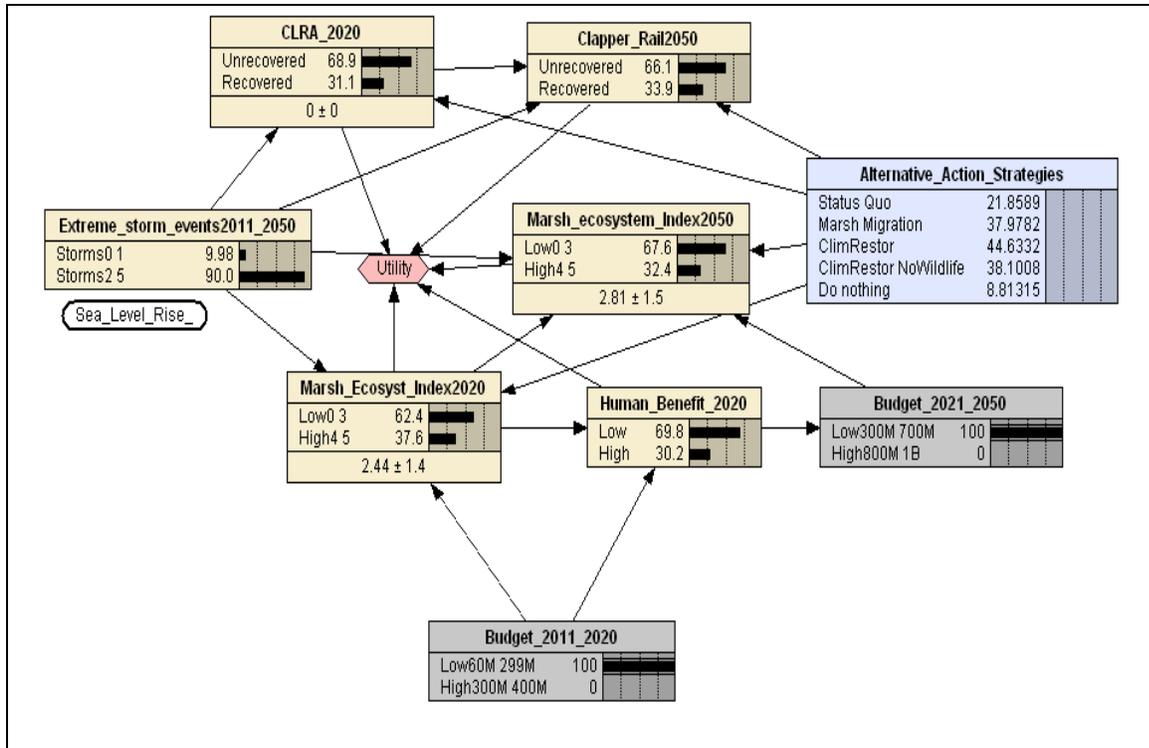


Figure 10: Bayes Net outcome diagram when both Marsh Ecosystem Index and Clapper Rail Recovery were predicted to have low levels in 2020 and 2050. All of the alternative allocations had similar and very low utility values (range: 6.6-6.8).

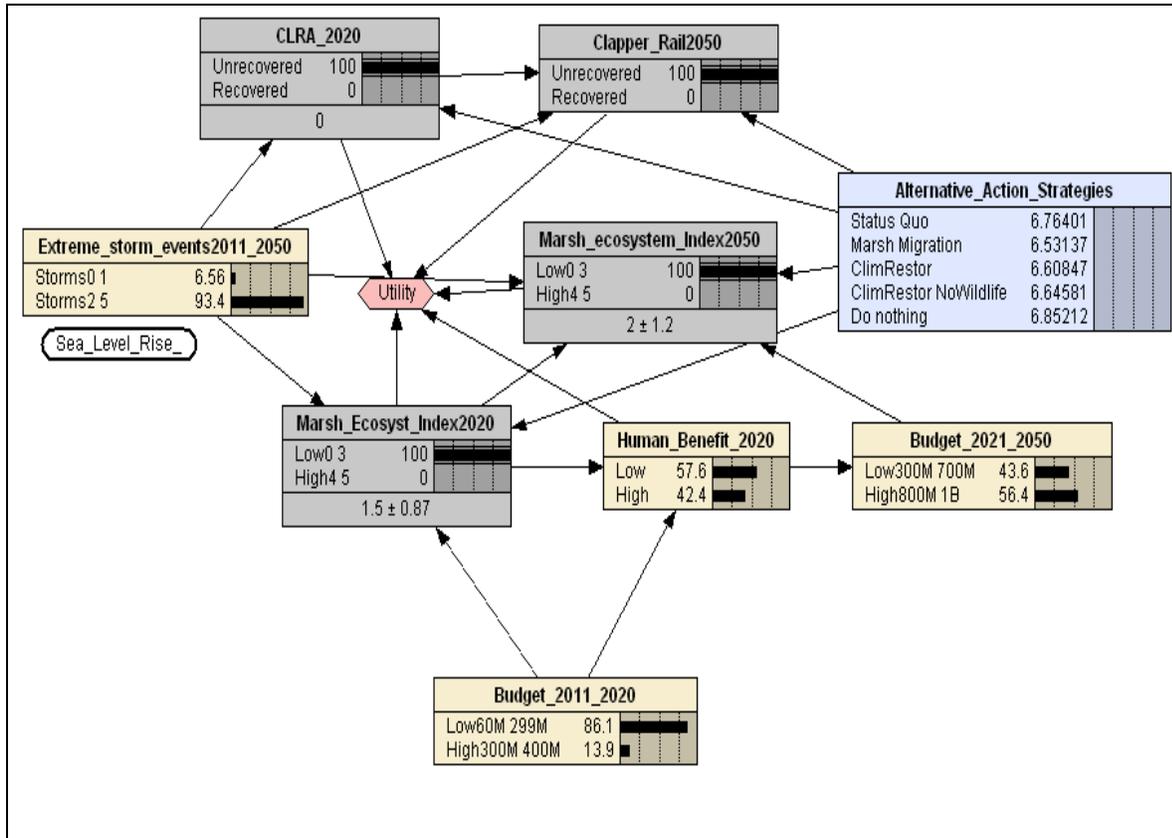


Figure 11A. Bayes Net outcome diagram with Climate Restoration Allocation as the chosen option.

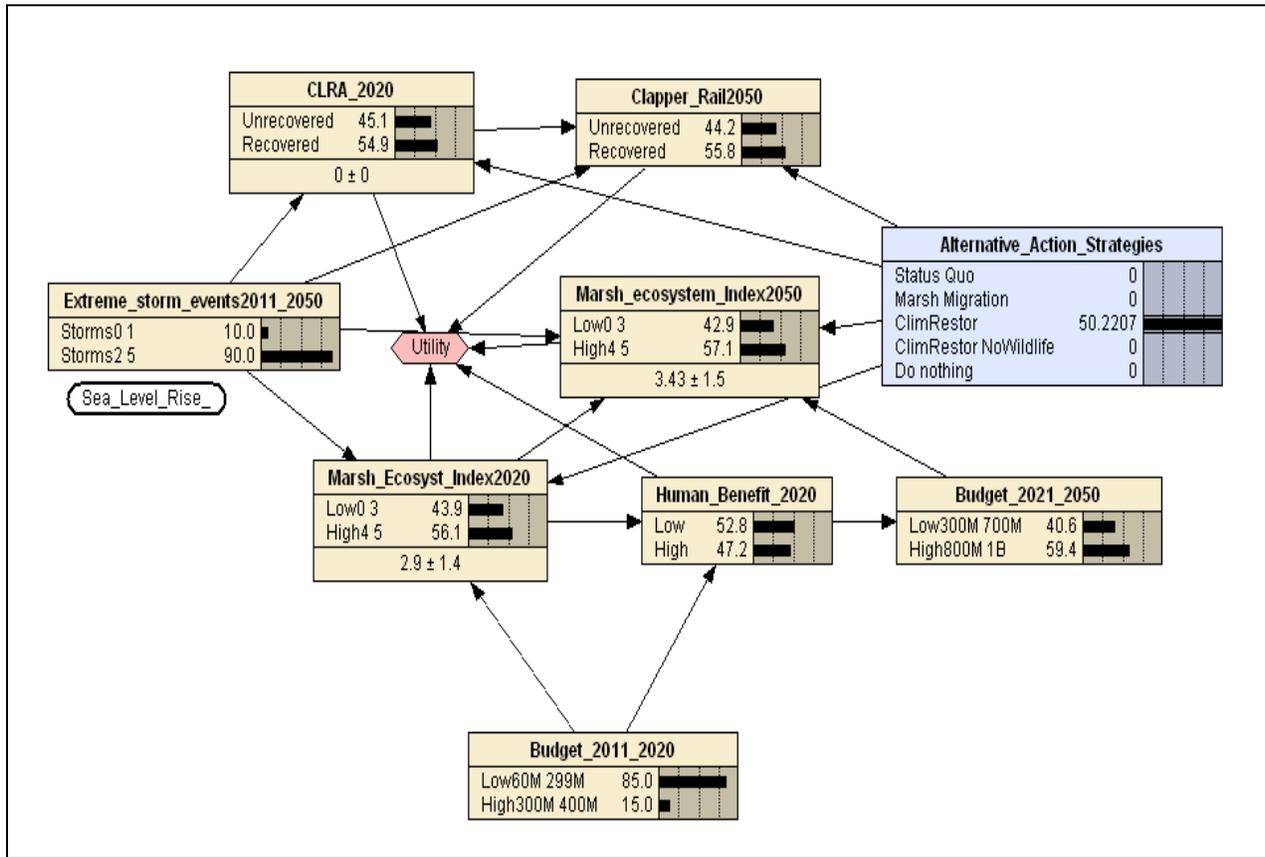


Figure 11B. Bayes Net outcome diagram with Marsh Migration Allocation as the chosen option.

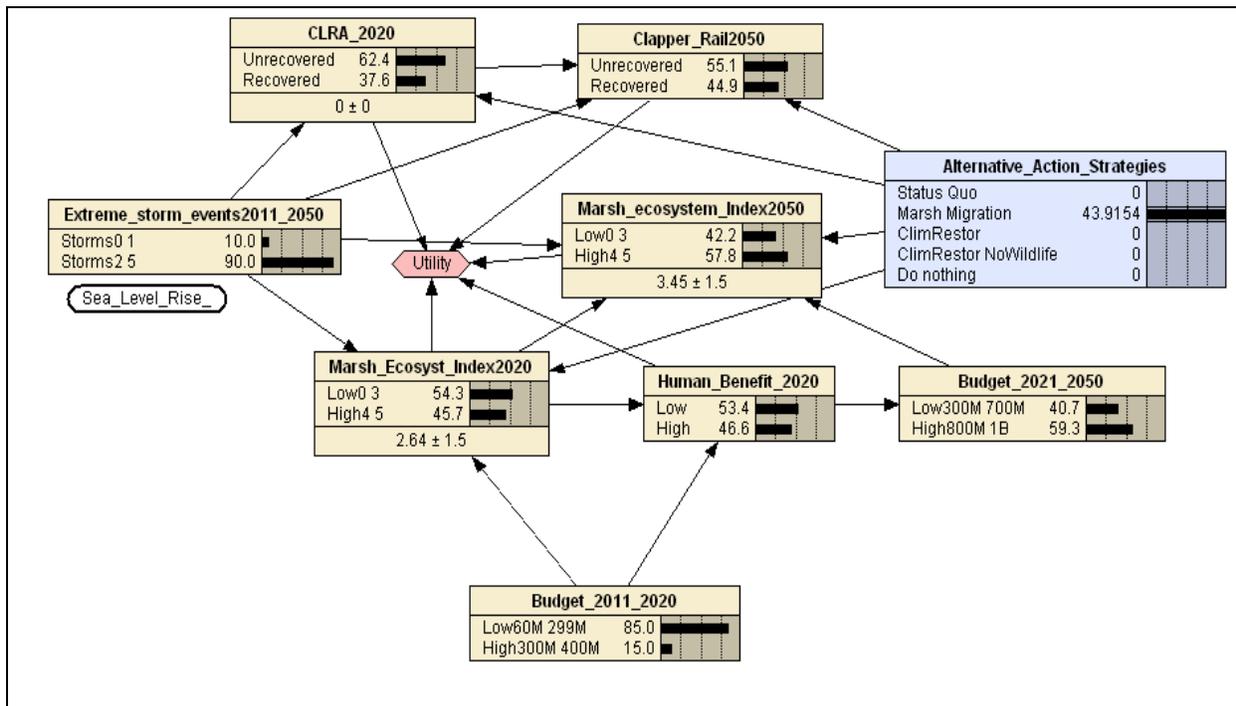


Figure 11C. Bayes Net outcome diagram with Climate Restoration + No Wildlife Allocation as the chosen option.

