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Vulnerability Assessments in Support of the Climate Ready Estuaries Program: A Novel Approach Using Expert Judgment

Volume II
Results for the Massachusetts Bays Program

United States Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment

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ABSTRACT

The Massachusetts Bays Program (MBP) and the Environmental Protection Agency (EPA) collaborated on an ecological vulnerability assessment, using a novel methodology based on expert judgment, to inform adaptation planning under EPA's Climate Ready Estuaries Program. An expert elicitation-type exercise was created to systematically elicit judgments from experts in a workshop setting regarding climate change effects on two key ecosystem processes within salt marsh systems: sediment retention and community interactions. Specific workshop objectives were to assess (1) the relative influences of physical and ecological variables that regulate each process, (2) their relative sensitivities under current and future climate change scenarios, (3) the degree of confidence about these relationships, and (4) implications for management. For each process, an influence diagram was developed identifying key process variables and their interrelationships (influences). Using a coding scheme, each expert characterized the type and degree of each influence to indicate its nature and sensitivity under current and future climate change scenarios. The experts also discussed the relative impact of certain influences on the endpoints. This report demonstrates how particular pathways in such diagrams can be linked to management options and examined in the context of planning documents to identify opportunities for 'mainstreaming' adaptation into strategic planning.

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LIST OF ABBREVIATIONS AND ACRONYMS

CCMP	Comprehensive Conservation and Management Plan
CCSP	Climate Change Science Program
CRE	Climate Ready Estuaries
CSO	Combined Sewer Overflow
EPA	Environmental Protection Agency
H	high
HH	high evidence/high agreement
HL	high evidence/low agreement
IPCC	Intergovernmental Panel on Climate Change
LH	low evidence/high agreement
LL	low evidence/low agreement
L	low
MBP	Massachusetts Bays Program
NECIA	Northeast Climate Impacts Assessment
OMWM	Open Marsh Water Management
ORD	U.S. EPA's Office of Research and Development

PREFACE

This report was prepared by the Global Change Research Program (GCRP) in the National Center for Environmental Assessment of the Office of Research and Development at the U.S. Environmental Protection Agency (EPA), in collaboration with the Massachusetts Bays Program (MBP) of the National Estuary Program (NEP). The report presents the results of a pilot, targeted, climate change vulnerability assessment for selected ecosystem processes of the Massachusetts Bays' salt marsh systems, using a new methodology based on expert elicitation techniques. Both the place-based results and the methodology itself are intended to support not only the MBP and the larger NEP community, but also other natural resource managers who are interested in adapting to the impacts of climate change on valued ecosystems.

The genesis of this project came from two sources. The first was a 2008 interagency report led by the EPA GCRP on behalf of the U.S. Climate Change Science Program, entitled *Adaptation Options for Climate-Sensitive Ecosystems and Resources*, which laid out general principles for understanding vulnerabilities and identifying adaptation approaches and called for refinement and application of these concepts through place-based activities. In that same year, EPA's Office of Water and Office of Air and Radiation launched a series of pilot projects under a new, Climate Ready Estuaries (CRE) program designed to provide targeted assistance to NEPs to assess climate change vulnerabilities and plan for adaptation. Based on the complementary nature of both efforts, the EPA GCRP joined forces with the CRE program to support two of its original pilot projects. These were collaborative vulnerability assessments with the San Francisco Estuary Partnership (the subject of Volume I of this two-report set) and the Massachusetts Bays Program (this Volume II report).

The Massachusetts Bays Program is a partnership of citizens, communities, and government that strives to protect and enhance the coastal health and heritage of Massachusetts and Cape Cod Bays. It was officially accepted as a U.S. National Estuary Program in 1990, based on its status as a nationally-significant estuary threatened by pollution, development, or overuse. As such, the MBP created a comprehensive conservation and management plan to ensure ecological integrity and protect valued resources such as coastal habitat, shellfish populations, and clean water. As a CRE pilot partner in 2008, the MBP was provided with technical support to begin a process to identify climate change vulnerabilities of these resources, develop adaptation plans and begin to implement selected actions within these plans. This project is a first step in this process. Starting with a kickoff meeting with local experts and stakeholders, the MBP/EPA team elected to focus the current vulnerability assessment on climate-sensitive salt marsh ecosystems, targeting a narrow subset of key physical and biological processes essential to salt marsh community health and maintenance.

This report presents the results of this pilot effort. It is intended as a proof of concept for a new type of assessment exercise rather than a comprehensive vulnerability assessment for the whole estuary. Thus the scope was designed for a deeper examination of the climate sensitivities of two selected processes—sediment dynamics and salt marsh sparrow habitat dynamics—that are integral to functioning salt marshes. Given the multidisciplinary assessment objectives and the limitations on available data and modeling tools, a new method based on expert elicitation was developed in order to capture the current understanding of the climate sensitivities of the system as a starting point for adaptation, which will be an iterative process as new ecosystem processes are added to the analysis and as our understanding of the climate and management impacts grows. We hope that this report will be a useful starting point for adaptation action and a methodological basis for future work on climate change vulnerability assessments for estuarine systems.

We would like to acknowledge the major contributions of ICF International, Inc. throughout this project, including conceptualization, methodology development, workshop support, and report production. Special thanks to Regina Lyons of EPA Region 1 for generous participation in the form of workshop coordination and venue, and internal technical reviews. We would also like to express our appreciation to John Wilson, John Whitler and Michael Craghan (EPA Office of Water), Jeremy Martinich (EPA of Air and Radiation), and the rest of the CRE team for their leadership, partnership and many useful discussions. We commend Jan Smith of the Massachusetts Bays Program for initiating this project through the CRE program, and the participants of the expert elicitation workshop for sharing their knowledge and judgments. We also appreciate the substantive contributions of our external and internal EPA reviewers. Finally, we would like to thank Mike Slimak, Anne Grambsch, and all of the EPA Global Change Research Program staff for their advice and numerous and significant inputs to this project.

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EXECUTIVE SUMMARY

The Massachusetts Bays estuaries are highly vulnerable to climate-related changes including changes in precipitation, altered hydrology, increased effects of winds and waves, and sea level rise. Impacts such as increased inundation of coastal wetlands, changes in water availability and quality, and altered patterns of sedimentation and erosion are increasingly interacting with other human stressors such as nutrient loading and land use changes. Thus it is essential that estuary managers become 'climate-ready' by: assessing the vulnerability of natural resources to climate change; choosing strategically among adaptation strategies in the near term; and engaging in longer term planning based on a range of plausible scenarios of future change. In an era of shrinking budgets coupled with increasingly complex decision-making needs—often taking place in a context of uncertainty and incomplete information—managing natural resources in the face of climate change will be challenging. There is a need for assessment methods that take advantage of existing scientific expertise to help identify robust adaptation strategies, weigh difficult trade-offs, and justify strong action, all in a timely and efficient manner.

The purpose of this project was to carry out a pilot vulnerability assessment for the Massachusetts Bays Program's (MBP) natural resources using expert judgment, the results of which could be linked to adaptation planning. To this aim, EPA's Office of Research and Development collaborated with MBP on a novel expert elicitation exercise for 'rapid' vulnerability assessment. A trial exercise was carried out during a two-day workshop in which two groups of seven experts each focused on two key salt marsh ecosystem processes: sediment retention and community interactions within salt marsh sharp-tailed sparrow nesting habitat (see Figure ES-1). The exercise, which was based on formal expert elicitation techniques but tailored specifically for qualitative analysis of ecosystem processes, was designed to glean expert judgments on the sensitivities of ecosystem process components under future climate scenarios. This was followed by group discussions of the implications of the results for management in light of climate change, as well as feedback on the exercise itself.

Sensitivities and Potential Adaptation Responses

Using the experts' judgments on the sensitivities of key ecosystem process components to future climate conditions, it is possible to identify 'top pathways' for which there are available adaptation options. After creating influence diagrams showing the relationships among key process variables (see Figures ES-2 and ES-3), the experts generated information on

Salt Marsh
Sediment Retention

The balance between the processes of removal and deposition of sediment

Community Interactions:
Saltmarsh Sharp-Tailed Sparrow Nesting Habitat

Interactions of native *Spartina* species and invasive *Phragmites* that determine sparrow nesting habitat

Figure ES-1. Selected ecosystem processes for the pilot vulnerability assessment.

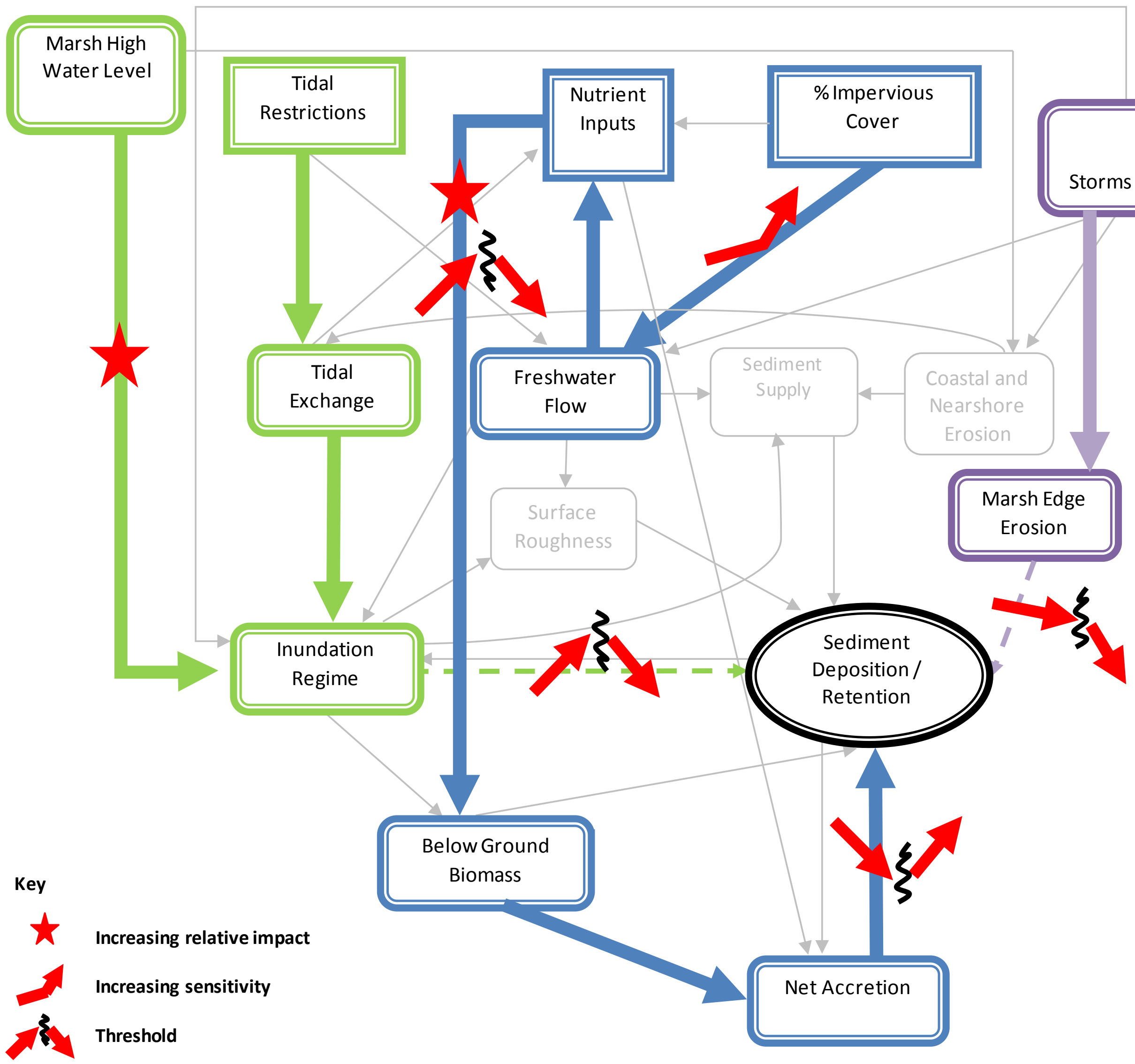

Figure ES-2. Top pathways for management of the Sediment Deposition/Retention endpoint. Colors are used to distinguish different pathways. Red symbols highlight potential changes under future climate conditions.

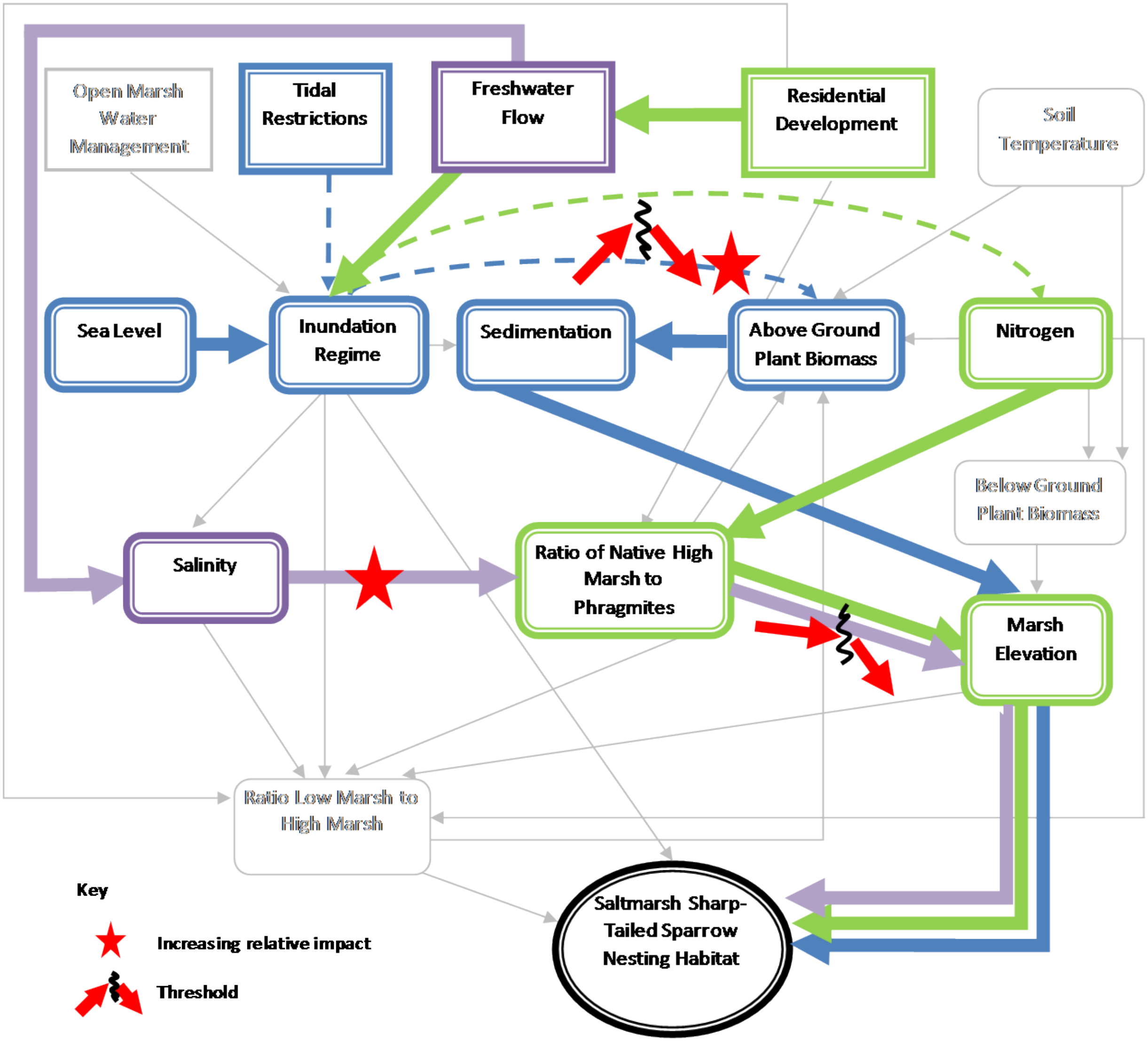

Figure ES-3. Top pathways for management of the Saltmarsh Sharp-Tailed Sparrow Nesting Habitat endpoint. Colors are used to distinguish different pathways. Red symbols highlight potential changes under future climate conditions.

which relationships may show, under future climate change (1) increasing relative impact on the overall process, (2) increasing sensitivity, and (3) abrupt threshold changes. Based on the amount of expert agreement on each relationship, it is possible to identify ‘top pathways’ of interest for management. Three top pathways for each process are described below, with accompanying discussion of adaptation options for management.

<u>Sediment Retention Purple pathway</u>: In this pathway (see Figure ES-2), the experts identified the potential for a threshold shift in the effect of marsh edge erosion on sediment deposition and retention, from a mild inverse effect to a much stronger inverse effect. Marsh edge erosion occurs when wave energy results in loss of sediment from the seaward edge of the marsh; under current conditions some sediment is redeposited in the marsh, but some is lost. Under climate change, increased storm intensity in conjunction with sea-level rise will expose the marsh edge to greater wave energy for longer periods of the tidal cycle. This will intensify sediment loss from the system as more sediment is carried out of the marsh, leading to an abrupt drop in sediment deposition and retention. Management options under this pathway include:

- Establishing “no wake” zones to reduce erosion due to boat wakes
- Protecting barrier beaches (which protect marshes during storms) through dune grass protection and restoration
- Developing new tools to reduce wave energy before it reaches the marsh edge, such as methods to establish oyster reefs adjacent to marshes
- Monitoring to detect threshold shifts, to identify areas losing sediment as priorities for action and to measure effectiveness of interventions

<u>Sediment Retention Green pathway</u>: This pathway (see Figure ES-2) contains a threshold shift in sediment deposition and retention in response to inundation regime (depth and duration of marsh flooding). Under current conditions, an increase in inundation leads to increased transport into, and deposition of sediment onto, the marsh. However, this relationship flips from a direct to an inverse effect under climate change, when sea level rise increases inundation to such an extent that increased tidal flow velocities suspend more sediment than is deposited, leading to a net decrease in deposition and retention. An increasing relative impact of sea level leads to this threshold through marsh high water level (the transition from marsh to upland vegetation). Given the significance of tidal restrictions in influencing inundation regime, this additional branch of the pathway has important implications for management. Options include:

- In the near term, relieving tidal restrictions to restore upstream hydrology, salinity and sediment transport, thereby supporting upland migration of marsh high water level
- In the longer term with sea level rise, using tide gates that can be closed prior to storms or spring tides to avoid peak flooding and associated high flow velocities during inundation
- Modifying ditches to restore more natural hydrology
- Removing barriers to upland migration such as roads and hardened shorelines
- Advancing policies and incentives that limit building of new barriers and encourage conservation easements and other protections

Sediment Retention Blue pathway: Climate-related changes are expected in three influences along this pathway (see Figure ES-2). Starting at the sediment deposition and retention endpoint, an increase in net accretion (net change in elevation) currently decreases sediment deposition by reducing flow velocities during inundation, such that much sediment drops out of suspension before making its way very far into the marsh; but with higher sea level under climate change, a threshold flip will occur where greater water depths during inundation result in higher flow velocities that carry suspended sediment further into the marsh. Net accretion is directly affected by below ground biomass, which is itself involved in a second threshold relationship with nutrient inputs. Nutrients currently have a positive effect on below ground biomass through stimulation of above ground growth; but under climate change this flips to a negative effect as excessive nutrients inversely affect below ground productivity and increase decomposition, with increasing relative impact on the end point. Finally, delivery of nutrients via freshwater flows is affected by percent impervious cover in the adjacent landscape; and the sensitivity of flows to impervious cover is expected to increase with climate change as storms and flashiness of precipitation events intensify. Management options under this pathway include:

- Improving stormwater management through the use of permeable pavements, rain catchers, and buffers
- Upgrading sewage treatment plants to include tertiary treatment
- Upgrading combined sewer overflow systems to ensure all sewage passes through upgraded treatment
- Engaging in public outreach to inform homeowners of the best timing, placement, and application rates for fertilizers

Community Interactions Green pathway: The climate-related shift examined in this pathway (see Figure ES-3) is the effect on marsh elevation of the ratio of native high marsh to invasive *Phragmites* (high marsh:Phrag). Marsh elevation is one of only three variables that feed directly into the nesting habitat endoint, and all of the top pathways converge on this one relationship. Currently, a decrease in high marsh:Phrag leads to a modest increase in marsh elevation because *Phragmites* is more effective at trapping sediment (due to large rhizomes at the marsh surface). This relationship strengthens under the climate scenarios as a threshold shift to a stronger inverse relationship. With increasing sea-level rise, *Phragmites* will be better equipped to maintain elevation and migrate landward to higher elevations while continuing to more effectively trap sediment in place, compared to native high marsh that would lose elevation rapidly. The remainder of the pathway includes the effect on high marsh:Phrag of nitrogen (which favors *Phragmites*) and the effect on nitrogen delivery of inundation affected by flows from residential runoff. Management options under this pathway include:

- Promoting more absorbent land cover (including permeable pavements)
- Upgrading treatment plants and improving stormwater management to reduce nutrient-rich runoff
- Creating incentives for decreased use of fertilizers on lawns, regular inspections of septic systems, and rain catchers to further reduce nutrient-rich runoff
- Coupling *Phragmites* control programs with removal of barriers to migration and protection of upland areas to allow native high marsh to expand as sea level rises

Community Interactions Purple pathway: Starting at the nesting habitat endpoint and working backwards, the Purple pathway (see Figure ES-3) corresponds with the Green pathway in its first two influences; so see above for discussion of the threshold effect of high marsh:Phrag on marsh elevation. The Purple pathway then diverges to focus on salinity's effect on high marsh:Phrag. Greater salinity inhibits *Phragmites* and thus has a direct positive effect on high marsh:Phrag, with high relative impact on nesting habitat. The high relative impact is due to a competitive interaction between salinity and nitrogen, where increased salinity has a negative impact on *Phragmites* while increased nitrogen has a positive effect. Salinity's high relative impact will increase more under climate change, as sea level rise leads to increased inundation of saline water for longer periods, higher into the marsh (placing greater pressure on *Phragmites*). Given the effect of freshwater flows (exacerbated by impervious surfaces in residential areas) in counteracting salinity maintenance, management options under this pathway include:

- Prioritizing the use of permeable pavements and rain catchers to reduce freshwater runoff, thereby helping to maintain natural salinity levels
- Controlling the hydrodynamic regime (e.g., through channel creation/ditch modification) to maintain salinity through unimpeded tidal inundation
- Restoring riparian buffers and upstream freshwater marshes to reduce freshwater flows and favor local infiltration and storage of rain water

Community Interactions Blue pathway: The Blue pathway (see Figure ES-3) focuses on marsh elevation from the perspective of sedimentation. Sedimentation directly affects marsh vertical accretion and is itself directly affected by above ground plant biomass as a source of organic sediment. Climate-related shifts occur in the way above ground plant biomass is affected by inundation regime (percent time high marsh is under water April−October). Currently, inundation regime favors above ground plant biomass since flushing via inundation prevents soil salinity from reaching levels that inhibit growth. Thus, just as an appropriate inundation regime is important for maintaining salinity (see Purple pathway above), it is also important for preventing salinity from becoming too high. Under climate change, however, this influence shifts from a direct to an inverse effect: as sea level rises, inundation frequency and duration are expected to reach levels that cause increased hypoxia and marsh die-back, with increasing relative impact on the endpoint. Management options under this pathway include:

- In the near term, restoring tidal connections (e.g., by removing tidal restrictions) to support appropriate inundation regimes
- In the longer term (at some point in the next 30−60 years with sea level rise), utilizing restrictions (e.g., through use of tide gates) to control flows appropriately
- Restoring native high marsh habitat in protected areas where marsh can grow and expand
- Prioritizing marsh restoration and protection activities in locations where natural flows and good sediment supplies are already in place

Based on the nature and timing of the sensitivity, some actions can be taken immediately while others require monitoring and planning for multiple potential futures. In the case of relationships that are well understood and for which there are management options available, the nature of an expected climate-related shift has implications for when managers may want to take action. In cases where the expected shift is toward increasing relative impact (and especially if the relationship is already of high relative impact today), actions can be taken immediately to implement management options to positively affect those pathways. In the case of relationships for which a change in sensitivity is possible under future climate scenarios, the expectation of increasing sensitivity should trigger further study of the relationship in order to anticipate the degree and timing of the impending sensitivity and prepare best management responses. Finally, thresholds are a particular challenge, as it is often impossible to predict exactly when a threshold change will happen. In these cases it will be important to monitor threshold variables to identify the shift when it occurs; in the meantime managers might act to keep the system 'below' the threshold as long as possible, while also preparing a plan for what to do when unavoidable shifts occur. After a shift occurs, managers may decide to manage the system differently in its new state, or take no action and instead shift priorities to other goals.

Adaptation Planning

Relating top pathways and associated adaptation options to existing management activities is a path forward for action. The top pathways described above were used to identify adaptation options that could be applied to sensitive ecosystem process components. Additional pathways and associated adaptation options can be further explored using the detailed tables of judgments and strategies provided in this report. The next step toward adaptation planning is to connect top pathways and adaptation options to existing management activities and plans.

Under its current goals, MBP is already undertaking a variety of activities that can be related to these adaptation options, as described in its annual, mid-term and long-term planning documents. These include specific restoration, nutrient management, monitoring and research projects and strategies. The climate change sensitivities and adaptation strategies identified in this report can be cross-referenced to activities and objectives in the Strategic and Annual Plans to identify where existing work can be adjusted to better support adaptation. Some examples of such cross-referencing are provided as a starting point for more comprehensive adaptation planning during future planning cycles. The broad goals and objectives articulated in the current Comprehensive Conservation and Management Plan (CCMP) allow for addition of new mid- and short-term actions; and the next revision of the CCMP will be an opportunity to incorporate new higher-level goals and objectives addressing climate impacts beyond sea level rise. The intent is that the results of this assessment will help inform priority investments in projects that take into account specific, known climate sensitivities and make use of particular adaptation options that will be most effective. The assessment results can also assist in priority-setting for long term research and monitoring investment and for partnership building with other organizations.

'Mainstreaming' climate change adaptation into ongoing, iterative planning processes will increase the ability of managers to identify win-win options, weigh multiple trade-offs, and prepare for long-term changes. For MBP as well as other National Estuary Programs and organizations with well established planning processes, there are benefits to 'mainstreaming' (continuously integrating) adaptation into ongoing planning, rather than developing a stand-alone adaptation plan. The aim is to start with actions that have multiple benefits, i.e., that contribute to current management goals while also responding to climate change. For example, the same activities that can protect shellfish resources by using stormwater best management practices for runoff reduction will also benefit wetlands by favoring native high marsh over invasive *Phragmites* under climate change. Since climate change also has the potential to intensify and even create new trade-offs, mainstreaming adaptation into planning will also be important for identifying and weighing conflicts among adaptation options within the context of existing (and emerging) goals.

Given the long-term nature of the climate change challenge, mainstreaming has an additional advantage over a stand-alone plan in that it helps counteract the tendency to postpone adaptation actions in the face of more immediate challenges. It often may be possible to adjust current practices in ways that achieve adaptation while still fulfilling original goals. An example of this is removal of tidal restrictions; current practices for restoring natural hydrology include reengineering the size of openings at road crossings to allow full tidal exchange. Tide gates have been used in other situations to allow the tide to pass in one direction but to restrict flow in the other. Installing tide gates in places where flooding may become a future problem is one way to adjust current practices since tide gates can be more actively managed (by opening and closing at particular times, such as during spring tides) to allow for full tidal exchange in some circumstances and restricted flow in others.

Finally, thinking ahead as part of planning is essential for anticipating which of today's best practices may become ineffective and even 'maladaptive' as sensitivities change and threshold shifts occur under climate change. Once thresholds have been crossed or other unavoidable changes of significance have occurred, some management goals may have to be revised. For instance, there may be a point in the future when the currently-beneficial effects of removing tidal restrictions will start to negatively impact certain habitat goals, necessitating reevaluation of this technique as a restoration practice.

Evaluation of Expert Judgment Approach

A novel methodology based on expert elicitation was developed and piloted as a tool for 'rapid assessment' of ecological sensitivities to climate change. The aim was to explore whether it is possible to synthesize useful information from experts on key climate sensitivities in the short time frame of a two-day workshop, using expert elicitation techniques. Expert elicitation is a multidisciplinary process for using expert judgment to inform decision making when data are incomplete, uncertainties are large, and multiple models can explain available data. The novel methodology introduced here is a modification of formal (usually quantitative) expert elicitation that uses qualitative judgments to explore complex ecological questions. Influence diagrams showing causal relationships among variables were used to capture the experts' collective understanding of selected ecosystem processes under current conditions and under two future (midcentury) climate scenarios. A coding scheme was used to record the judgments, with observational notes and group discussions used to gather additional information.

The result was three categories of information based on the influence diagrams: (1) the direction and strength of the relationships among variables, (2) the changing sensitivities (including potential threshold responses) to climate change of some relationships, and (3) the relationships of highest relative impact on the process as a whole. When this wealth of information is combined into a 'crosswalk' of all three categories, it is possible to identify top pathways (see above) comprised of relatively well-understood relationships that are sensitive to climate change and for which management options are available. Managers are encouraged to further 'mine' the tables for other key pathways applicable to their specific sites and to identify potential research priorities based on information gaps.

The expert elicitation exercise developed for this assessment has the potential to be useful for other sites, processes, and ecosystems. While an example Great Marsh site was used as a means to focus the exercise, the variables that ended up in the final influence diagrams are common enough that most of the results may apply to other Massachusetts Bays marshes as well. It is likely that the influence diagrams also could be transferred for use with corresponding ecosystem processes in other northeast estuaries, with minor revisions for place-specific stressors or other process variables; however, the characterizations of variable relationships, sensitivities and relative impacts would have to be revised, particular to the location. Where information on completely different processes is needed, the general methodology should be transferable to other processes and ecosystems. The strengths of this method include its ability to capture more recent knowledge than would be available from a literature review and more knowledge of the type that is closely related to management. It is also effective at integrating across disciplines and scales, which is particularly important for ecosystem and climate change assessments.

As a proof of concept for a new type of assessment exercise, this method and the pilot results come with a number of caveats. This was not a comprehensive vulnerability assessment for the whole estuary, so prioritization based on these results should be considered in the broader context of other vulnerable processes, ecosystems, and goals. Given the complexity of these systems and instances of uneven agreement among experts, actions based on the top pathways should be taken with care, with each manager considering the applicability of the information to his or her own specific system. Confidence estimates for individual judgments turned out to be challenging, so improvements have been suggested for strengthening this aspect in future assessments. There is also the potential to simplify the coding scheme based on what was learned in this trial run, to improve efficiency and allow experts more time to fill in data gaps. Regardless, the expert elicitation method developed for this study was well suited for achieving the goals of this assessment, and in a time frame much shorter than would be required for more traditional, detailed quantitative modeling. Having a well-supported and timely study to substantiate new and existing ideas on adaptation can position managers to justify the most appropriate management priorities. It also can validate research priorities by highlighting known research gaps. Overall, the method offers opportunities to capture and integrate the existing collective knowledge of local experts, while pushing the boundaries to develop a new understanding of the system and identify robust adaptation options in the face of climate change.

1. INTRODUCTION

1.1. BACKGROUND

The estuaries of the Massachusetts Bays are highly vulnerable to the impacts of climate change. Sea level rise, increased temperatures, changes in precipitation, and changes in storm climatology are already causing increased inundation of coastal wetlands and marshes, changes in water availability and quality, and altered patterns of sedimentation and erosion (Scavia et al., 2002; Fitzgerald et al., 2008). These impacts are interacting with other anthropogenic stressors such as tidal restrictions and increased impervious land cover to make management of estuarine ecosystems more challenging than ever. While there are many uncertainties regarding the nature of future climate changes and the response of ecosystems to those changes, estuary managers can 'ready' themselves by assessing the vulnerability of natural resources to climate change, making strategic choices about how to implement adaptation strategies[1] in the near term, and planning for longer term management under a range of plausible scenarios of future change. It is the aim of U.S. Environmental Protection Agency's (EPA's) Climate Ready Estuaries (CRE) Program to assist National Estuary Programs in meeting such information and planning needs.

As part of the CRE Program, the Massachusetts Bays Program (MBP) and EPA's Office of Research and Development (ORD) collaborated on the design and trial of a novel methodology for conducting vulnerability assessments for sensitive ecosystems of the Massachusetts Bays. The aim was to develop assessment capabilities using expert judgment to synthesize place-based information on the potential implications of climate change for key ecosystem processes, in a form that would enable managers to link the resulting information to adaptation planning.

1.2. PURPOSE AND SCOPE

1.2.1. Purpose

The purpose of this project was two-fold: to conduct a vulnerability assessment using a novel, expert judgment approach based on expert elicitation methods, and to analyze the implications for adaptation planning. This was not a comprehensive vulnerability assessment for the whole estuary but rather a proof of concept for a new type of assessment exercise, using two key ecosystem processes of salt marsh ecosystems as demonstration studies. This was accomplished through a series of steps to: (1) identify key management goals and ecosystem

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[1] Throughout this report, "adaptation" refers to management adaptation rather than evolutionary adaptation. Management adaptation refers to strategies for the management of ecosystems in the context of climate variability and change (CCSP, 2008a).

processes essential to meeting those goals; (2) create conceptual models of selected ecosystem processes; (3) assess ecosystem process sensitivities to climate change; (4) consider resulting vulnerabilities with respect to management goals; and (5) explore implications for adaptation planning. Steps 1−2 were used to define the scope of the assessment, while steps 3−5 comprise the vulnerability assessment itself.

1.2.2. Scope

The scoping process began with a review of the MBP Comprehensive Conservation and Management Plan in order to select key management goals upon which to focus the assessment. The key ecosystem-related goals selected by MBP in consultation with EPA ORD were to:

- Protect and manage existing wetlands
- Restore and enhance the habitat diversity and living resources of wetlands
- Protect submerged aquatic vegetation
- Prevent the spread of marine invasive species in order to maintain biodiversity

After an information-sharing meeting with local experts to discuss the project and learn about climate change impacts and adaptation work in the region, salt marshes were selected as the focal ecosystem for study. Salt marshes were identified as highly relevant to MBP's management goals due to their ecological productivity, their habitat values for vulnerable species, their susceptibility to ongoing encroachment by invasive species, and their sensitivity to changes in climate-related variables such as sea level rise and altered hydrology. For more detailed information on goal and ecosystem selection processes, please see Appendix A.

The second step in the scoping process was the development of a conceptual model to understand the primary drivers and processes of salt marshes. The conceptual model was used to explore the linkages among key ecosystem processes within the ecosystem, major stressors of concern, and climate drivers causing altered or new stressor interactions. The model was refined to a set of six key ecosystem processes that are essential to the maintenance of salt marsh systems, as identified through literature review of salt marsh conceptual models and climate change impacts. Based on this general conceptual model, two specific processes of concern were selected for further analysis. The purpose was to select good processes for piloting the method, but the choice does not imply that these are necessarily the most important or the most vulnerable processes. The processes were selected in consultation with MBP staff, based on the criteria of being integral to MBP's management goals, increasingly sensitive to climate change, and sufficiently well-studied by the scientific community to provide the basis for a more in-depth assessment.

The two processes selected for further analysis were sediment retention and community interactions. Sediment retention, which refers to the balance between the processes of removal and deposition of sediment onto a salt marsh, was selected because of its importance for marsh development and growth. The topic of community interactions was narrowed to a tractable "storyline" involving several key species; it was selected based on discussions with local experts on the MBP staff. The storyline selected was the relationship of marsh vegetation zonation (between native *Spartina* and invasive *Phragmites* grasses) and the availability of nesting habitat for the Saltmarsh Sharp-Tailed Sparrow (see The IUCN Red List of Threatened Species; http://www.iucnredlist.org/). Expanded submodels were developed for each of the two processes and served as the basis for designing the sensitivity analyses of the subsequent expert elicitation exercise. For more detailed information on process selection and conceptual model development, please see Appendix A.

The remaining steps of the assessment—the sensitivity analysis, vulnerability assessment, and analysis of management implications—were accomplished through an expert elicitation-style workshop, the results of which make up the core of this report. Expert elicitation is a multidisciplinary process using expert judgment to inform decision making when empirical data are incomplete, uncertainties are large, more than one conceptual model can explain available data, and technical judgments are required to assess assumptions. It takes advantage of the vast amount of local knowledge that is available via regional experts who are familiar with the state of the science for the system of interest. During a two-day workshop, a novel application of the expert elicitation method was tested using two groups of seven expert participants each. A list of the expert participants for each breakout group is provided in Table 1-1. The experts were selected based on criteria that ensured extensive expertise in the local system, broad coverage of multiple scientific disciplines, experience in both science and management, and knowledge of both empirical and theoretical research (for additional information on participant selection criteria and credentials, please see Appendix B). The participants assessed the sensitivities of salt marsh sediment retention and community interactions to climate- and nonclimate stressor interactions, with an eye toward informing adaptation strategies. The methodology and results of this expert elicitation exercise are described in the sections that follow.

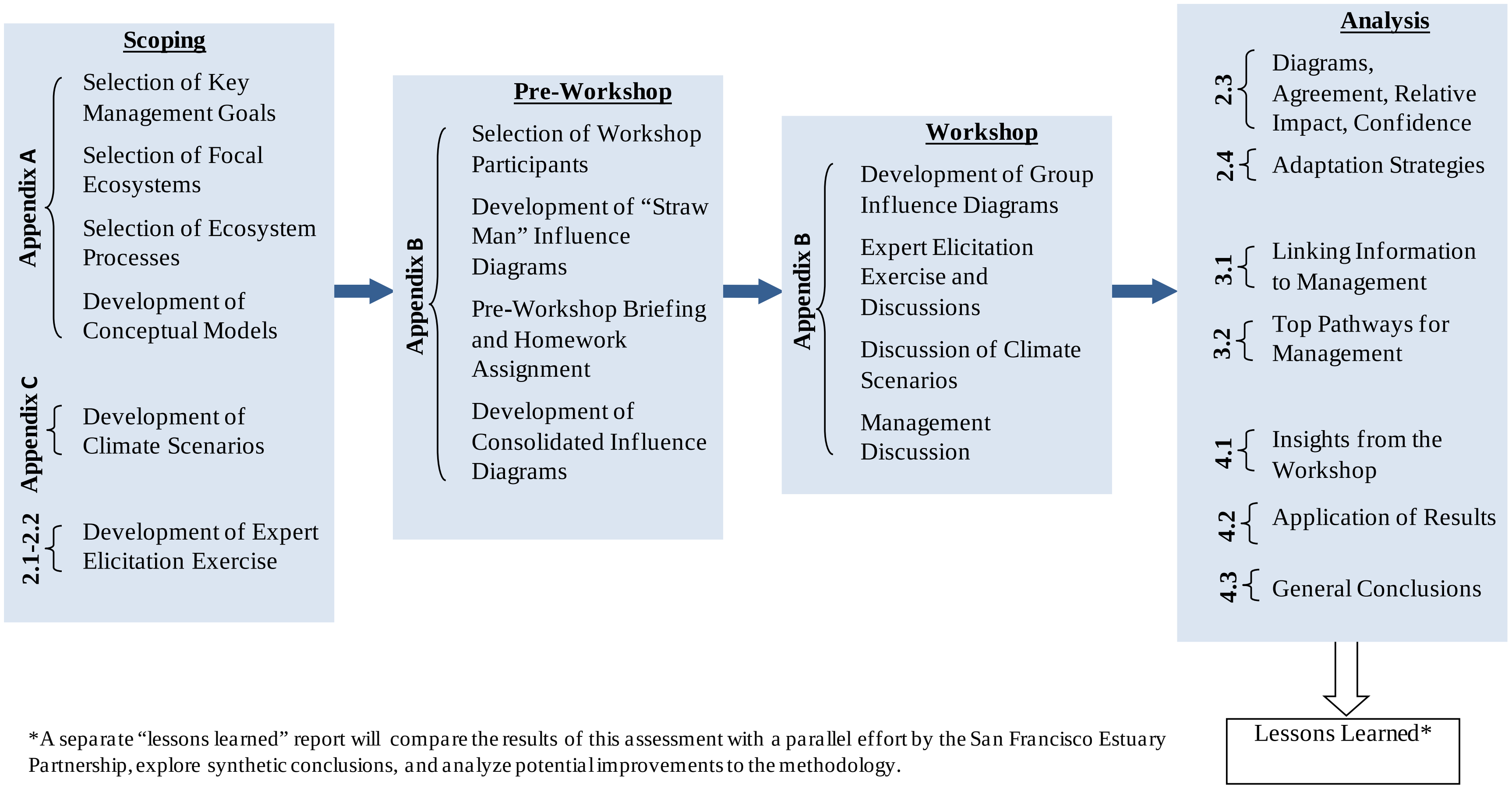
Table 1-1. Breakout group participants for the expert elicitation workshop (see Appendix A for further details on selection criteria and credentials)

Sediment retention group	Community interactions group
Susan Adamowicz Rachel Carson National Wildlife Refuge	**Walter Berry** U.S. EPA Atlantic Ecology Division
Britt Argow Wellesley College	**Robert Buchsbaum** Massachusetts Audubon Society
Chris Hein Boston University	**Dave Burdick** University of New Hampshire
David Ralston Woods Hole Oceanographic Institution	**Michelle Dionne** Wells National Estuarine Research Reserve
John Ramsey Applied Coastal Research and Engineering	**David Johnson** Woods Hole Marine Biological Laboratory
Peter Rosen Northeastern University	**Gregg Moore** University of New Hampshire
John Teal Woods Hole Oceanographic Institute	**Cathy Wigand** U.S. EPA Atlantic Ecology Division

1.3. ROADMAP FOR THE REPORT

This report presents a summary of the entire project, including CCMP goal selection and conceptual modeling, the expert elicitation methodology, the results of the workshop, and implications for management. Figure 1-1 provides a flow chart of the assessment process and report structure.

Section 2 describes the expert elicitation exercise, including the approach, the exercise, and the results. Section 3 provides an analysis of the results with respect to how they may be used by estuary managers to understand ecosystem responses to climate change and engage in adaptation planning. Section 4 provides key conclusions of the assessment. The appendices provide additional detailed information on the activities conducted prior to and following the workshop. Appendix A summarizes the goal selection and conceptual modeling processes used for scoping the vulnerability assessment. Appendix B provides details on the expert elicitation preworkshop preparations and postworkshop follow-up, including expert selection criteria, preworkshop preparations by participants, and expert feedback. Appendix C and Appendix D contain detailed information that was provided to the participants on the development of climate scenarios and the methodology for estimating confidence.



*A separate "lessons learned" report will compare the results of this assessment with a parallel effort by the San Francisco Estuary Partnership, explore synthetic conclusions, and analyze potential improvements to the methodology.

Figure 1-1. Vulnerability assessment process.

2. EXPERT ELICITATION EXERCISE

2.1. JUSTIFICATION FOR METHOD

2.1.1. Definition and Uses

Expert elicitation is a multidisciplinary process for obtaining the judgments of experts to characterize uncertainty and fill data gaps where traditional scientific research is not feasible or adequate data are not yet available. The goal of expert elicitation is to characterize each expert's beliefs about relationships, quantities, events, or parameters of interest. The expert elicitation process uses expert knowledge, synthesized with experiences and judgments, to produce conclusions about the nature of, and confidence in, that knowledge. Experts derive judgments from the available body of evidence, including a wide range of data and information ranging from direct empirical evidence to theoretical insights.

Because EPA and other federal regulatory agencies are often required to make important national decisions in the presence of uncertainty, EPA's Science Policy Council formed an Expert Elicitation Task Force in April of 2005 to investigate how to conduct and use this method to support EPA regulatory and nonregulatory analyses and decision-making. The result was an Expert Elicitation Task Force White Paper that affirms the utility of using expert elicitation and provides recommendations for expert elicitation "best practices" based on a review of the literature and actual experience within EPA. The draft paper (see http://www.epa.gov/spc/expertelicitation/index.htm) is currently under external peer review through EPA's Science Advisory Board. The best practices outlined in the draft White Paper formed the basis for the design of this project's expert elicitation-style workshop.

2.1.2. Novel Application

The specific elicitation exercise used in this assessment was custom-designed by Dr. Max Henrion of Lumina Decision Systems, Inc. Dr. Henrion is a nationally-recognized authority on decision analysis methods and tools, dealing with uncertainty in environmental risk assessment, and expert elicitation (e.g., Morgan and Henrion, 1990; Henrion et al., 1991; Pradhan et al., 1996). As a member of EPA's Expert Elicitation Task Force, he was uniquely qualified to assist in designing a novel application of expert elicitation methods for use in a two-day workshop format. Specifically, Dr. Henrion developed a qualitative coding scheme for expert judgments about the sensitivity of ecosystem processes to physical and ecological variables, using "influence diagrams" to depict the relationships among ecosystem process variables and external drivers such as climate change. This new methodology, described in detail below, explores the utility of expert elicitation for conducting “rapid vulnerability assessments” for ecological systems.

2.2. WORKSHOP DESIGN AND METHODOLOGY

2.2.1. Workshop Goals and Objectives

The overarching goals of the workshop were to: (1) improve the understanding of the sensitivity of salt marshes to the projected impacts of climate change; (2) improve the ability to identify adaptation management strategies that mitigate the impact of climate change in salt marshes, given the uncertainties; and (3) demonstrate the applicability of an expert elicitation approach to this type of analysis.

The workshop was held April 27−28, 2010, in Boston, MA, at the EPA Region 1 office. During the workshop, experts were divided into two breakout groups to consider each ecosystem process separately. The seven participants in each breakout group (see Table 1-1) were asked to provide judgments about the ecosystem process under consideration by their group. For each ecosystem process, the specific workshop objectives were to: (1) characterize the relative influences of physical and ecological variables that regulate the process; (2) assess the relative sensitivity of the ecosystem process to key stressors under current conditions and future climate scenarios; (3) assess the degree of confidence in judgments about these relationships; and (4) relate the results of the exercise to adaptation planning through group discussions. Given the range of habitats and issues in the entire Massachusetts Bays area, the participants were asked to consider Jeffrey’s Neck Marsh (Great Marsh System; see Figure 2-1) when a more specific spatial scope would be useful during the workshop exercise, as well as when considering management implications. However, issues and options that were not specific to Jeffrey’s Neck Marsh were also considered during group discussions.

For further details on workshop preparation and implementation, including selection criteria for participants and details on Jeffrey’s Neck Marsh, please see Appendix B.

2.2.2. Approach and Methodology

According to protocols put forth in EPA’s Expert Elicitation Task Force White Paper, there are a variety of options for gathering and processing expert judgments. The specific elicitation approach used in this workshop was one that asked experts to give their individual judgments independently. This was done to reduce the tendency towards “group-think,” i.e., the tendency for many people to go along with the most vocal participant, even if s/he is not the most knowledgeable. Participants had an opportunity to make adjustments to their judgments at any time during or after group discussions; however, consensus was *not* the goal of the exercise.

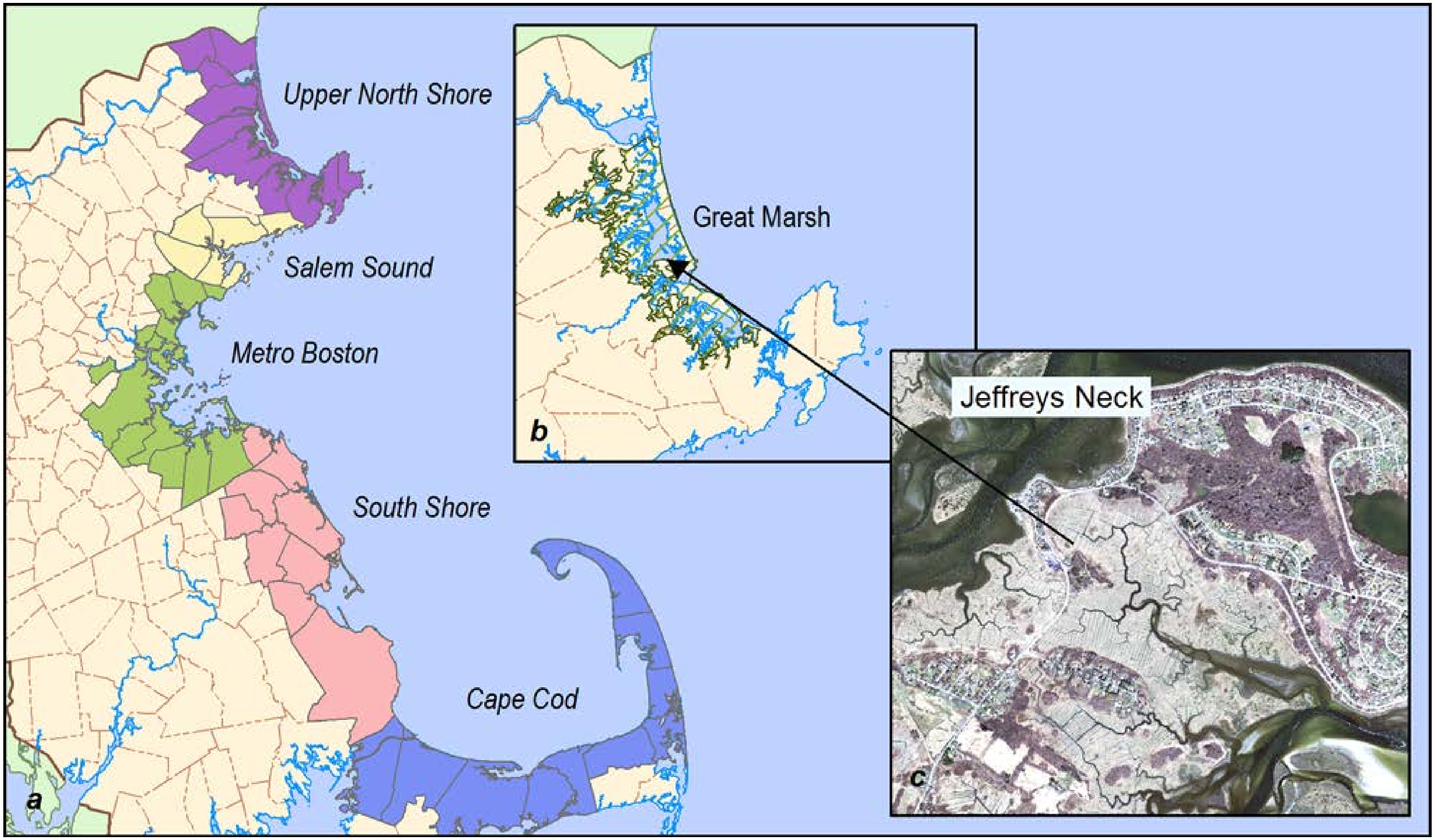


Figure 2-1. The Massachusetts Bays. (a) The five regions of the Massachusetts Bays Program planning area; (b) The Great Marsh Area of Critical Environmental Concern; and (c) Jeffreys Neck salt marsh.

Rather, the aim was to look at the expert judgments in aggregate, while also retaining information on variance in judgments. This approach is well-suited to the type of qualitative judgments participants were asked to make at the workshop.

2.2.2.1. *Influence Diagrams*

Each breakout group participated in the development of an influence diagram of the ecosystem process under consideration by their group. Decision analysts use influence diagrams as a way to define the qualitative structure of causal relationships among variables that experts believe are of greatest importance for understanding the problem being evaluated. Influence diagrams typically represent a subset of a larger, more detailed model such as the conceptual models developed previously (see Appendix A).

A simplified influence diagram for sediment retention is provided in Figure 2-2. By convention, the variables in an influence diagram are represented by rectangles (labeled boxes) while arrows between the variables represent causal relationships, or “influences” (labeled with letters). Sequences of arrows form pathways, all of which ultimately lead to the final variable, or endpoint, of concern. In Figure 2-2, the endpoint that is being evaluated is sediment deposition/retention. Interactive effects of multiple variables on each other, or on the endpoint, can occur where two “causal” variables both influence (have arrows into) a common “response” variable. In Figure 2-2, an example interaction is indicated by arrows C and D, where freshwater flow and coastal and nearshore erosion together could have an interactive effect on sediment supply.

In the case of community interactions, the influence diagram was constrained to a tractable number of species of interest for study. It focused on the relationship of marsh vegetation (native *Spartina* and invasive *Phragmites* grasses) and the resulting availability of nesting habitat for the Saltmarsh Sharp-Tailed Sparrow. The Saltmarsh Sharp-Tailed Sparrow prefers the native, upper marsh species *Spartina patens* for nesting habitat. This habitat is being infringed upon by invasive *Phragmites* from the landward side, and by lower marsh *Spartina alterniflora* (which is migrating upland with sea level rise) from the seaward side. Please see Appendix A for a more detailed explanation of this storyline.

While influence diagrams are widely used and relatively well understood, our proposed use of qualitative degrees of influence is an innovation in expert elicitation. Typically, an expert elicitation seeks to obtain expert judgments about uncertain quantities in the form of numerical probability distributions. For the ecosystem processes considered during this workshop, there were information, data, and time limitations that made quantifying the influences as probability distributions unrealistic. Instead, judgments were based on qualitative types (is the relationship

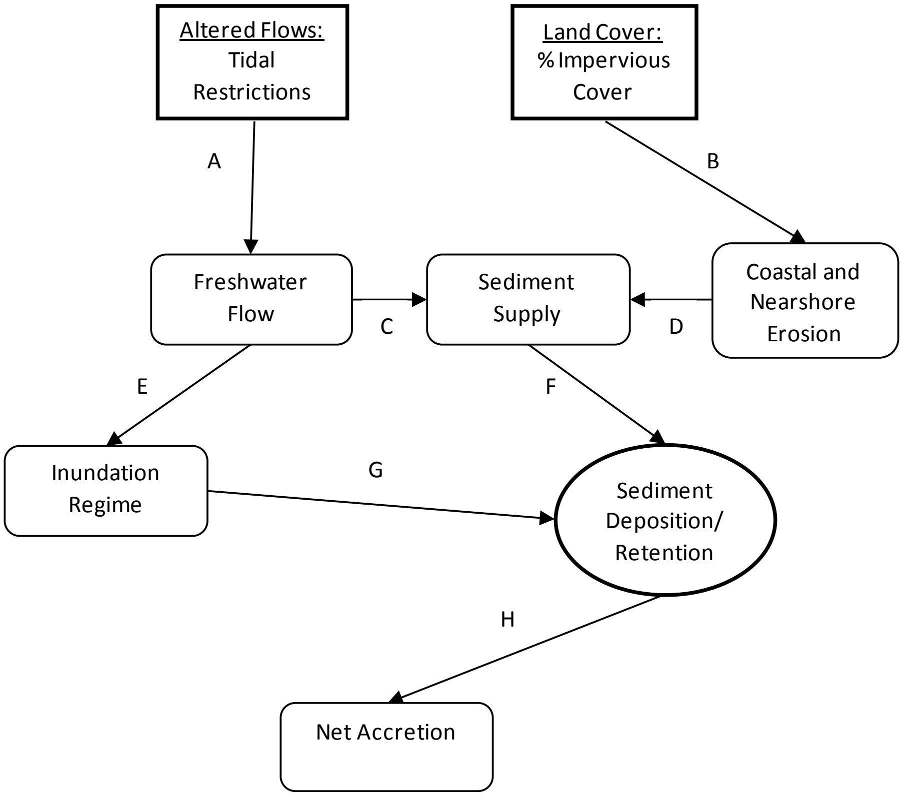


Figure 2-2. Simplified influence diagram for sediment retention.

direct or inverse?) and degrees (is the response small or large?) of influences. The use of qualitative degrees of influence provides much more detail than simply specifying causal influences with arrows alone, but less specificity than required for quantified probabilities.

Prior to the workshop, the participants attended briefing calls in which they: learned about the project plan; discussed background reading materials; and were presented with “straw man” diagrams (see Appendix B) developed from the original conceptual models. They were asked to review the diagrams and submit their own revised versions the week before the workshop. Diagram submissions were combined into one consolidated draft diagram for each group that served as the starting point for discussion at the workshop. The workshop itself began with each group working together to refine their diagram into a “group diagram”. The group influence diagram was meant to distill the system to a tractable set of key variables and influences, and as such it was not comprehensive. The groups were given complete freedom to alter any part of the diagram, with the exception of the ecosystem process endpoint, as long as they constrained the diagram to a total of no more than 15 boxes. At the same time, participants were reminded to keep some of the top row stressor or management boxes, since these would serve as key linkages back to management options. Participants were also encouraged to minimize the total number of arrows in the diagram to include only the most key influences. The purpose was to capture the key components and relationships of each ecosystem process in a concise form that could be rapidly assessed in a workshop setting. Once the group diagrams were finalized, all of the participants made their judgments using the same diagram throughout the remainder of the workshop.

2.2.2.2. *Climate Scenarios*

Dr. Katharine Hayhoe of Texas Tech University, an experienced climate scientist with an extensive background in regional climate assessments, developed two climate change scenarios for use in the expert elicitation exercise (see Appendix C for more detailed information on the climate change scenarios). The scenarios represented two distinct but scientifically credible climate futures for a mid-century (2040−2069) time period. (The mid-century time frame was selected by the MBP partners because of its suitability for adaptation planning.) The projections were based on six leading climate models, using a lower emissions scenario (Climate Scenario A) and a higher emissions scenario (Climate Scenario B) to generate values for climate variables for use by the experts in making their judgments (see Table 2-1).

Under both climate change scenarios, Massachusetts will experience a significantly warmer climate, accompanied by increases in annual precipitation and higher sea levels. By mid-century, the “higher-range” Climate Scenario B (which includes higher emissions and a more sensitive climate) is projected to experience a warmer and somewhat wetter climate compared to the “lower-range” Climate Scenario A (with lower emissions and a lesser impact on Massachusetts climate).

At the workshop, Dr. Hayhoe provided the participants with an overview of major climate drivers and regional trends for Massachusetts. She discussed five main sources of uncertainty with climate projections, including: (1) the amount of future emissions; (2) the degree to which the influence of global climate change on local climate is modified by local factors; (3) the sensitivity of the climate system (as feedbacks are not well understood); (4) the ability of climate models to simulate climate both globally and locally; and (5) the natural variability of the climate system. Because of these factors, exact predictions of climate change are not possible. However, uncertainty can be dealt with by using multiple scenarios to bracket a range of plausible climate futures and identify key vulnerabilities in the system. In order to consistently “bound” the consideration of future climate changes in the workshop exercise, the participants were instructed to use the values provided under Climate Scenarios A and B (see

Table 2-1. Summary of Climate Scenario A (“lower-range” scenario) and Climate Scenario B (“higher-range” scenario): averages for midcentury

		“Lower-range” scenario (3-model average of B1)*	**“Higher-range” scenario (3-model average of A1Fi)***
Temperature	Annual average	+3.6°F	+5.6°F
	Geographically	Boston “moves” to Philadelphia, PA	Boston “moves” to Washington, DC
	Days > 90°F[a]	20 days	34 days
	Coldest day of year	+4.3°F	+6.5°F
	Growing season	+3 weeks	+4 weeks
Precipitation	Winter change	+10.6%	+15.1%
	Summer change	+7.9%	+11.2%
	Spring change	+15.0%	+14.1%
	Fall change	+1.9%	−2.2%
	Heavy events	~8% increase in the max amount of precipitation to fall within a 5-day period	~12.5% increase in the max amount of precipitation to fall within a 5-day period
	Yearly snow depth	−9 cm	−11 cm
Sea level	Total increase	17 cm [Sea Level Affecting Marshes Model (SLAMM) model A1B scenario]	41 cm (SLAMM mid-century model estimate using 1.5 m scenario by end of century)[b]
Storms/wind		Northeast Climate Impacts Assessment (NECIA, 2006) suggests little change in the frequency of winter-time storms for the East Coast. However, under the “higher range” scenario, between 5 and 15% of these storms (an additional one storm per year) will move northward during late winter (Jan, Feb, March), affecting the Northeast. (No change for the “lower range” scenario.) In addition, the impact of a higher sea level will increase the likelihood of storm damage to coastal locations. For hurricanes, the most current understanding is that rising sea surface temperatures will increase evaporation, increasing the amount of rainfall associated with any given hurricane, but there is too much uncertainty in projections of hurricane frequency and wind intensity to say much about future trends.	
Ice-out		2 weeks earlier	4 weeks earlier
Spring peak flow period		7 days earlier	10 days earlier
Summer low flow period		1 week longer	2 weeks longer
Drought[c] frequency		2 every three years (compared to 1 every two years today)	
Winter flooding events		two-fold increase in number of events	
General increases in salinity of estuarine waters, freshwater tributaries, and coastal aquifers during summer			
*Please refer to Appendix C for more information on the development of the climate scenarios.			

[a] Compared to the 1960−1990 annual average of 9 days with temperatures above 90°F.

[b] The total difference in range between mean and spring tides of 1.3 ft (39.6 cm) is very close to the higher emission scenario rise of 41 cm. Based on data for Plum Island Sound (south entrance), the spring high tide is generally 0.65 ft (19.8 cm) higher than the mean high tide. http://tidesandcurrents.noaa.gov/tides10/tab2ec1b.html#8.

[c] Defined as the monthly soil moisture is more than 10% below the long-term mean (relative to historic simulations).

Table 2-1) to contextualize their judgments about future effects on the ecosystem processes under consideration. For additional details on the climate scenarios, including data sources, please see Appendix C.

2.2.2.3. *Expert Facilitation*

Due to the highly technical nature of the exercise, the complexity of the novel methodology that was being used, and the ambitious time line for accomplishing multiple outputs, it was essential that the workshop be run by skilled expert facilitators. The expert facilitators selected were Brock Bernstein, Independent Consultant and President, National Fisheries Conservation Center and Carlton Hunt, Research Leader with Battelle in Duxbury, Massachusetts. They were chosen based on a number of criteria including: proven expertise in facilitating science-based workshops; general knowledge of science behind estuary management (particularly wetlands ecology); and experience working on national coastal issues and/or issues in the Massachusetts Bays region. Dr. Hunt is an experienced and trained facilitator who has been working in Massachusetts Bay for several decades, and has served as the project manager and technical lead on Battelle's Massachusetts Water Resources Authority program. Dr. Bernstein is a marine ecologist with research experience in a range of coastal and oceanic environments and has worked on a wide variety of management and policy issues. Dr. Hunt served as the facilitator for the Sediment Retention group, while Dr. Bernstein served as the facilitator for the Community Interactions group.

Prior to the workshop, both facilitators attended training calls in which they were fully briefed on the project background and conceptual models, the workshop goals and objectives, and the expert elicitation exercise. Working together and with the MBP/EPA team, the facilitators contributed to the refinement of the workshop agenda and improvements to the workshop process.

2.2.2.4. *Coding Scheme and Exercise*

Participants were asked to characterize each influence in their influence diagram according to the coding scheme presented in Table 2-2. Influences were characterized first under current conditions, and then under Climate Scenario A and Climate Scenario B. The extent to which participants agreed in their judgments was variable across the different influences. The rule that was adopted for determining agreement for each influence was that a majority (four or more participants) had to have selected the same code. As this was not a consensus process, and the small group size limited statistics that could be done, majority was chosen as the most simple rule as a basis for agreement. A case could be made for a more restrictive rule on what

Table 2-2. Coding scheme used during the workshop exercise to characterize influences. "Small" and "large" changes in variables are defined relative to the current range of variation for each variable, with "small" indicating that the variable is within its current range of variation and "large" indicating that the variable has moved outside its current range of variation

Option	Type and degree of influence definition
0	No influence: we know that changes in X have no effect on changes in Y, holding all other variables constant.
1	Unknown influence: we don't know whether an increase in X will increase, decrease, or have no effect on Y.
2	Proportional increase: a large increase in X is likely to cause a large increase in Y. A small increase is likely to cause a small increase.
3	Proportional decrease: a large decrease in X is likely to cause a large decrease in Y. A small decrease is likely to cause a small decrease.
4	Inverse decrease: a small increase in X is likely to cause a small decrease in Y. A large increase in X is likely to cause a large decrease in Y.
5	Inverse increase: a small decrease in X is likely to cause a small increase in Y. A large decrease in X is likely to cause a large increase in Y.
6	A small increase in X is likely to cause a large increase in Y.
7	A small increase in X is likely to cause a large decrease in Y.
8	A large increase in X is likely to cause a small increase in Y.
9	A large increase in X is likely to cause a small decrease in Y.
10	A small decrease in X is likely to cause a large increase in Y.
11	A small decrease in X is likely to cause a large decrease in Y.
12	A large decrease in X is likely to cause a small increase in Y.
13	A large decrease in X is likely to cause a small decrease in Y.

constitutes agreement, but that would obscure the understanding of many of the influences. Agreement among four or more participants was considered to indicate substantial agreement across the group.

Participants were also asked to characterize interactive influences of their choosing (i.e., those they deemed important), under current conditions and under the climate change scenarios, according to the coding scheme presented in Table 2-3. Since participants were given the option to choose which interactive influences they considered significant and to provide judgments only

Table 2-3. Coding scheme used during the workshop exercise to characterize interactive influences

Interactive influence	Definition
Independence	The effect of X on Y is independent of Z (default situation)
Synergy	The effect of X on Y increases with increase in Z
AND Gate	The effect of X on Y happens only with large Z
NOR Gate	The effect of X on Y happens only with small Z
Competition	The effect of X on Y decreases with increase in Z

for those influences, and were limited by time, there were often interactions where only one or two participants provided judgments. Only interactions scored by three or more participants were examined in order to focus on interactions judged by several participants to be significant. Three or more corresponding judgments were used to define agreement for interactive influences.

Finally, the participants were asked to assess their current level of scientific confidence in their judgments for each influence or interactive influence using the confidence coding scheme presented in Table 2-4. For each influence, each participant was asked to rate his confidence in his judgment based on: (1) the amount of scientific evidence that is available in the scientific community at large to support the judgment; and (2) the level of agreement/consensus in the scientific community at large regarding the different lines of evidence that would support the judgment. The coding options for “amount of evidence” were high (H) or low (L), based on whether available information is abundant and well-studied and understood, versus sparse and mostly experimental/theoretical. The coding options for “level of agreement” were H or L, based on whether data, reports, and experience across the scientific community reflect a high or low level of agreement about the influence. Thus it was possible to have four combinations of evidence and agreement when assessing confidence: high evidence, high agreement (HH), high evidence, low agreement (HL), low evidence, high agreement (LH), and low evidence, low agreement (LL). The rule for determining agreement in confidence was the same as described above for influences: agreement was defined as a majority (four or more) of the same categorization of confidence level. Similarly using the same rule as above for interactive influences, agreement on confidence for interactive influences was defined as three or more of the same categorization of confidence. For additional details on the method used to assess confidence, please see Appendix D.

Table 2-4. Coding scheme used during the workshop exercise to characterize confidence

Confidence	Definition
LH	Low evidence, high agreement = established but incomplete
LL	Low evidence, low agreement = speculative
HH	High evidence, high agreement = well established
HL	High evidence, low agreement = competing explanations

2.2.2.5. *Typologies for Understanding Influences and Sensitivities*

2.2.2.5.1. Type and degree of influence

The group's level of understanding of the different influences (arrows) in the influence diagram can be gauged by the amount of agreement in participants' selection of influence codes. Sometimes participants agreed on the type of influence, but not necessarily the degree (strength) of the influence. Codes 2−13 (see Table 2-2) represent different combinations of types and degrees of influences that can be grouped according to the following typology:

Types:
Direct relationship (when X increases, Y increases) = Codes 2, 3, 6, 8, 11, 13
Inverse relationship (when X increases, Y decreases) = Codes 4, 5, 7, 9, 10, 12

Degrees:
Proportional response of Y to X = Codes 2−5
Disproportional response of Y to X = Codes 6−13

Codes can also be paired according to the same type and degree of influence, with the only distinction being whether one is considering "X" to be increasing or decreasing. For example 2/3 is a direct proportional influence, with 2 indicating when "X" increases, and 3 indicating when "X" decreases, but in both cases "Y" is responding in a directly proportional way. Six combinations of pairings are possible:

Pairings by type and degree of influence (where “X” can go up or down):
Direct proportional = 2/3
Inverse proportional = 4/5
Direct disproportional, strong response (xY) = 6/11
Direct disproportional, weak response (Xy) = 8/13
Inverse disproportional, strong response (xY) = 7/10
Inverse disproportional, weak response (Xy) = 9/12

In some cases, participants selected the same exact code, indicating that they had the same understanding of the influence in terms of both type and degree. Or, sometimes participants chose pairings such as 2/3 while their colleagues may only have noted a 2 or a 3; we consider these cases to also indicate a correspondence in understanding of type and degree of influence, since the only distinction was whether a participant was thinking of “X” as going up or down (or both).

In another group of cases, there was agreement on the type of influence (i.e., whether X affects Y directly or inversely), although there was lack of agreement on the degree of that influence. These latter cases amount to an understanding of how X affects Y, just not the magnitude. It may still be useful for management to know for which influences we at least have some understanding of the type of response, even if we are not sure of the magnitude.

Finally, there were cases in which there was such a mixture of codes selected as to indicate no agreement in either type or degree of influence. This indicated that, among this group of experts, the influence was poorly understood or poorly defined.

2.2.2.5.2. Sensitivity

It is also possible to establish a typology for assessing the sensitivity of each influence (i.e., how sensitive variable Y is to changes in X), especially with regard to how those may change under the climate scenarios. Several codes can indicate the same level of sensitivity, so the following groupings were used to indicate three levels of sensitivity:

Low sensitivity = Codes 8−9 and 12−13
Intermediate sensitivity = Codes 2−5
High sensitivity = Codes 6−7 and 10−11

This typology was used to document all judgments, along with the following additional categories of judgments:

No Influence = Code 0
Unknown influence = Code 1
None given = No judgment provided
Other = Response provided that does not fit into the coding scheme

2.2.2.6. *Understanding Relative Impacts of Influences*

While the coding scheme described above captures the nature of individual influences, it is also of interest to identify which influences and interactions the participants perceived to have the greatest relative impact on the ecosystem process endpoint. Here we define relative impact as the combination of not only sensitivity but also how greatly the variable is changing relative to other variables. Because relative impact is an emergent property that results from considering all influences in the diagram together, there was no coding for this in the workshop exercise; rather, this concept was explored through group discussions that looked at the influence diagram as a whole and identified influences of greatest relative impact in the context of the entire web of influences. During group discussions that spanned both days of the workshop, information was gleaned as to which influences participants perceived to have comparatively greater effects on the ecosystem process endpoints, and whether this varied under the climate scenarios. These discussions were captured in the workshop notes as well as in the influence diagrams, in which the participants identified influences and interactions of highest relative impact (see Sections 2.3.1.4 and 2.3.2.4).

2.2.2.7. *Key Questions*

As described above, there are three categories of information that together comprise the collective understanding of each ecosystem process as represented by its influence diagram: (1) the type and degree of influences between variables, (2) the sensitivity of “response” variables to changes in “affecting” variables, and (3) the relative impact of each variable on the ecosystem process endpoint. For each of the three categories of information, the following key questions are addressed.

Types and Degrees of Influences:

- For which influences and interactions was there agreement in participants' judgments (codes), and what were those codes?
- How did agreement on influences and interactions vary from current conditions to Climate Scenario A and Climate Scenario B?
- For influences and interactions for which there was agreement in judgments, how did confidence levels across the participants vary? Did this change under the climate scenarios?

Sensitivity of Influences:

- For which influences and interactions is there greatest sensitivity and least sensitivity in the response variable to changes in the "affecting" variable?
- Were there any influences or interactions where agreement on sensitivity across participants increased or decreased under the climate scenarios?

Relative Impact of Influences:

- Which influences and interactions did the participants indicate have the greatest relative impact on the ecosystem process endpoints?
- Were there any influences or interactions for which relative impact changed under the climate scenarios?

Using the data from the coding exercise as well as information that emerged during group discussions, these questions are explored in the results sections that follow.

2.3. RESULTS

Major outputs of the expert elicitation exercise included the group influence diagrams, the judgments on influences (including interactive influences) along with their confidence estimates, information on sensitivities (including thresholds), and characterizations of relative impacts. For the purpose of this study, a threshold is defined (as per Groffman et al., 2006) as a point at which there is an abrupt change in an ecosystem property (such as a flip in influence type from direct to inverse), or where a small additional change in a driver produces a large response (such as a shift from a proportionate to a disproportionately strong response of variable Y to a change in variable X).

2.3.1. Sediment Retention

2.3.1.1. *Group Influence Diagram*

Figure 2-3 shows the group diagram developed by the Sediment Retention group. Variable definitions that were developed by the participants during the construction of the diagram are found in Table 2-5. The diagram highlights the balance of erosion and accretion processes in determining the Sediment Deposition/Retention endpoint. On the erosion side, Marsh Edge Erosion directly impacts the endpoint, while Coastal and Nearshore Erosion include impacts of erosion outside the marsh. Erosion from external sites can serve as a sediment source to the marsh and so acts through Sediment Supply, as well as impacting Tidal Exchange as erosion changes basin bathymetry and the resulting hydrodynamics. Both erosion variables are impacted by Storms, while Coastal and Nearshore Erosion is also influenced by Marsh High Water Level. Marsh High Water Level integrates sea level, topography and vegetation in that it is the transition between marsh and upland vegetation that is responsive to sea level, which is dependent on topography through slope.

On the accretion side, Net Accretion accounts for the accretion component directly, and is a two-way influence on the endpoint. Below Ground Biomass and Surface Roughness also influence accretion related processes, the former accounting for below-ground accretion, the latter for above ground accretion. Surface Roughness is another integrative variable. The characteristics of different grass species have differing impacts as water flows through them, which influences the deposition and retention of sediment. Inundation Regime is another two-way influence on the endpoint, one that can contribute to either accretion or erosion on the marsh surface. The diagram shows a high degree of interconnectivity between variables, especially among these accretion-related variables.

In addition, there are several feedback loops with the endpoint, including through Net Accretion and Inundation Regime. Inundation regime is itself influenced by multiple other variables, including Marsh High Water Level and Storms, as well as Tidal Exchange and Freshwater Flow. The management related variables at the top of the diagram include Nutrient Inputs, Altered Flows: Tidal Restrictions, and Land Cover: Percent Impervious Cover. Storms and Marsh High Water Level are additional stressor variables that are less clearly connected to management-related variables. The management options for Marsh High Water Level are one step removed and related to maintaining transitional uplands for upslope migration. These top level variables influence middle level ones which are primarily physical and hydrologic in nature. These include Tidal Exchange, Freshwater Flow, Sediment Supply, Coastal and Nearshore Erosion and Marsh Edge Erosion. Freshwater Flow and Inundation Regime both influence Sediment Deposition/Retention through Surface Roughness.

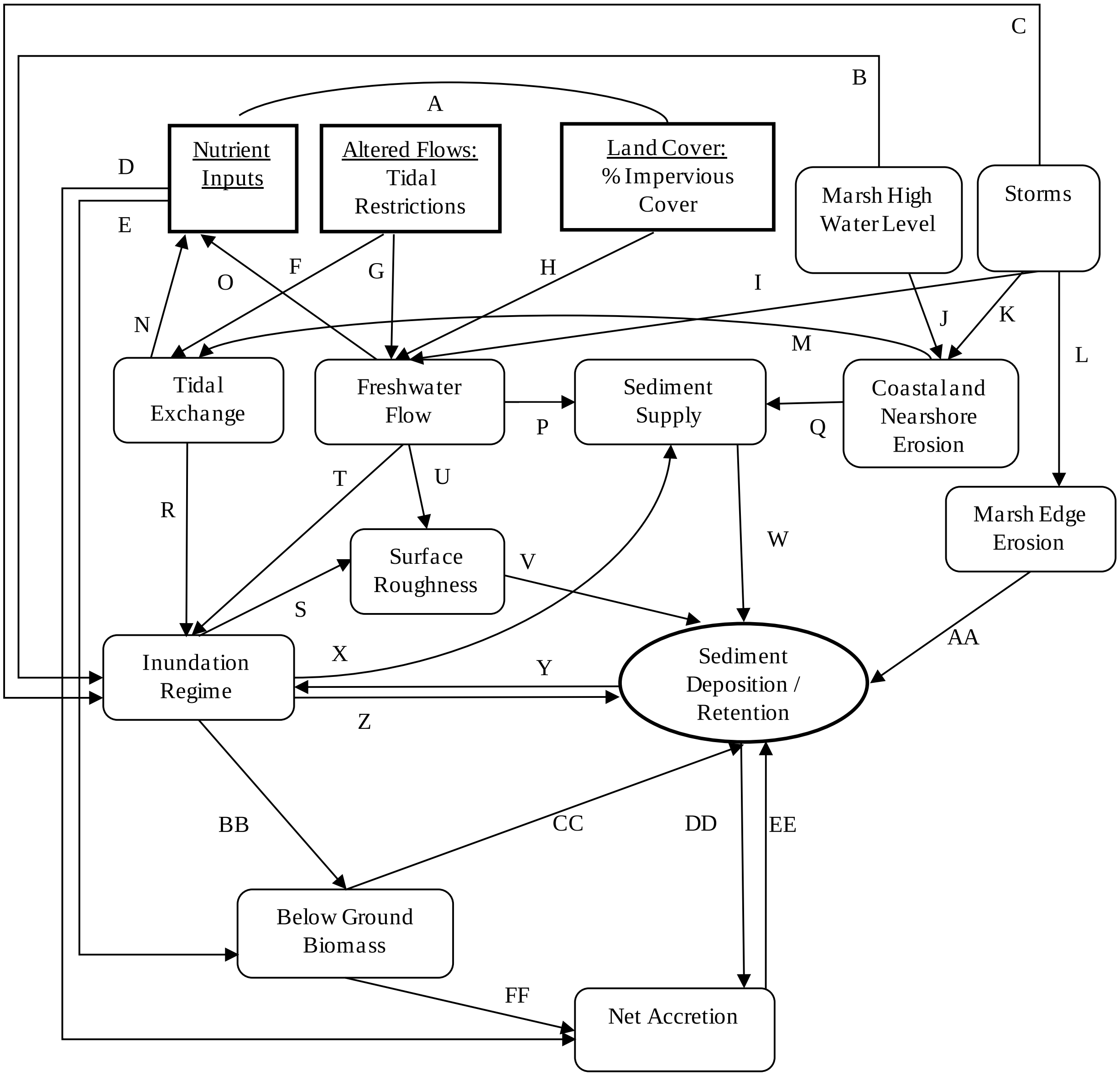


Figure 2-3. Sediment Retention group influence diagram.

Table 2-5. Sediment Retention variable definitions

Variable	Definition agreed upon by group
Nutrient Inputs	Annual loading rate (of Nitrogen and Phosphorous)
Altered Flows: Tidal Restrictions	Percent reduction compared to unrestricted flow
Land Cover: Percent Impervious Cover	Percent impervious cover
Marsh High Water Level	High tide limit, measured by where marsh vegetation changes to upland vegetation—includes integrated sea level
Storms	Frequency and intensity of (severe) storms
Tidal Exchange	Tidal prism
Freshwater Flow	Rate of freshwater inflow to the estuary from the watershed
Sediment Supply	External sources (terrestrial and marine) of inorganic material feeding the marsh, as measured by mass flux
Coastal and Nearshore Erosion	Net volume of eroded sediment from coastal zone
Surface Roughness	The interaction of stem density, height and diameter (based on plant species characteristics) with hydrodynamic regime
Marsh Edge Erosion	Volume of peat calved off marsh edges
Inundation Regime	Frequency, depth, and duration of marsh flooding
Below Ground Biomass	Below-ground biomass accumulation rate
Net Accretion	Net elevation change
Sediment Deposition / Retention	Amount per year (e.g., mm/yr)

2.3.1.2. *Influence Types and Degrees*

2.3.1.2.1. Agreement

The influences upon which participants agreed with respect to type and degree help to establish the nature of those relationships and indicate which are best understood. Table 2-6 presents these results for the Sediment Retention group.

In some cases, participants gave multiple codes for an arrow. When the multiple codes represented one of the pairing types described above in Section 2.2.2.4 (e.g., 2/3), both codes are shown, separated by a “/”.

If multiple codes that do not fall into a pairing were given, both codes are shown, separated by a symbol indicating the nature of the combination. In the first type of combination, multiple codes with “X” going in the same direction (e.g., X is increasing in both codes) are separated by a “^” symbol; and where these codes conflict and would make a difference in determining agreement, those cells were not counted. In the second type of combination, codes with “X” going in different directions (e.g., X is increasing in one code and decreasing in the

Table 2-6. Sediment Retention group influence judgments. Columns A−Z represent individual influences (arrows) in the influence diagram and rows represent individual respondents: dark green = agreement on influence type and degree, light green = agreement on type but not degree, gray = no agreement; within columns, green numbers = same (majority) grouping of type (though degree may be different), pink numbers = disagreement about type, red outline = threshold response

Current	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Resp. 1	2^6	2	2	9	2	2^6	0	2^6	2^6	6	6	6	2	12	6	2^8
Resp. 2	2/3	6|3	8^9	1	7	2/3	4/5	2/3	2/3	6|3	2	2/3	8/13	4/5	2/3	2/3
Resp. 3	2/3	2/3	2/3	4/5	2/3	4/5	0	2/3	2/3	2/3	2/3	2/3	8/13	1	2/3	2/3
Resp. 4	0	2	2	4	7	4	1	2/3	2	6	2	2	2	9	9	2
Resp. 5	6	8	6	9	6	7	0	6	6	6	6	1^6	8	6	2	2
Resp. 6	2	2	2	8	2	2	0	8	2	2	2	8	9	9	2	8
Resp. 7	2	2	2	5	4	4	0^3	2	2	2	2	2	0^2	4^6	2	2
Climate A	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Resp. 1	2	2	2	2^9	9	2^6	0	2^6	2^6	6	6	6	2	5	6	2^8
Resp. 2	2/3	6	2	0^4	7	4	4/5	6	6	6	6	2	8		2	8
Resp. 3	2/3	2/3	2/3	1	2/3	4/5	0	2/3	2/3	2/3	2/3	2/3	8/13	1	2/3	6/11
Resp. 4	0	2	2	4	7	4	1	2/3	2	6	2	2	1	2^9	2^9	2
Resp. 5	6	6	6	9	4	7	0	6	6	6	6	6	0	6	8	8
Resp. 6	2	2	2	8	2	2	0	8	2	2	2	8	9	9	2	8
Resp. 7	2	2	2	5	4	2		2	2	2	2	2	0^2	4^6	2	2
Climate B	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Resp. 1	2^6	2	2^6	2^9	9	2^6	0	6	6	6	6	6	2	5	6	2^8
Resp. 2	2/3	2	8	0^4	7	4	4/5	6	6	6	6	2	8		2	8
Resp. 3	2/3	2/3	2/3	1	2/3	4/5	0	2/3	2/3	2/3	2/3	2/3	8/13	1	2/3	6/11
Resp. 4	0	2	2	4	7	4	1	2/3	2	6	2	2	1	2^9	2^9	2
Resp. 5	6	6	6	9	4	7	0	6	6	6	6	6	0	8	8	8
Resp. 6	2	2	2	8	2	2	0	8	2	2	2	2	2	9	2	8
Resp. 7	2	2^6	2^6	5	4	2		2^6	2^6	2^6	2^6	2^6	0^2^6	4^6	2	2

Table 2-6. Sediment Retention group influence judgments. Columns A−Z represent individual influences (arrows) in the influence diagram and rows represent individual respondents: dark green = agreement on influence type and degree, light green = agreement on type but not degree, gray = no agreement; within columns, green numbers = same (majority) grouping of type (though degree may be different), pink numbers = disagreement about type, red outline = threshold response (continued)

Current	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF
Resp. 1	2^8	2	2^6^7	0^2	0^2	2	2^6	2^6	4	2^4	2^4	2^4	2	2	4	2
Resp. 2	1^2	6	2/3	2/3	1	2/3	4^6	0	4/5	2^4	4/5	1	6/11	2/3	2/3	2/3
Resp. 3	2/3	2/3	1	8/13	1	2/3	2/3	2/3	4/5	2/3	4/5	1	2/3	2/3	4/5	2/3
Resp. 4	2	2	1	2	2	2	2	2	4	2	1	9	2	2	5	3
Resp. 5	8	2	0	9	0	6	2	0	0	2	8	2	1	3	1	2
Resp. 6	2	2	9	8	8	8	2	1	9	2^4	4	2	2	2	4	2
Resp. 7	2	2	1	1	1	2	2	2	5	2^4	2	2^4	4	2^4	4	2
Climate A	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Y**	**Z**	**AA**	**BB**	**CC**	**DD**	**EE**	**FF**
Resp. 1	2^8	2	2^7	0	2^4	2^4	2^6	0	4	2^4	4	2^4	8	2	4	2
Resp. 2	1	6		2		2	2/3		0	2^4	4	2	8	2/3	2/3	8
Resp. 3	2/3	2/3	1	8/13	1	6/11	2/3	2/3	4/5	2/3	4/5	1	2/3	2/3	4/5	2/3
Resp. 4	2	2	4	8	1	2	2	2	4	2	1	9	2	2	5	3
Resp. 5	8	8	2	6	2	6	2	0	0	2	8	1	1	2	2	2
Resp. 6	2	2	9	8	8	2	2	1	0	2^4	4	3		2	2	
Resp. 7	2	2	4	1	1	1^2	2/3	2	5	2^4	2^4	2^4	2^4	2^4	4	2
Climate B	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Y**	**Z**	**AA**	**BB**	**CC**	**DD**	**EE**	**FF**
Resp. 1	2^8	2	2^7	0	2^4	2^4	6	0	4	2^4	4	2^4	8	2	4	2
Resp. 2	1	6		2		2	2/3		0	2^4	4	4	8	2/3	2/3	8
Resp. 3	2/3	2/3	1	8/13	1	6/11	2/3	2/3	4/5	2/3	4/5	1	2/3	2/3	4/5	2/3
Resp. 4	2	2	4	8	1	2	2	2	4	2	1	9	2	2	5	3
Resp. 5	8	8	2	6	2	6	2	0	0	2	8	1	1	2	2	2
Resp. 6	2	2^4	4^9	8	8	2	2	1^2	6	2^4	4	3		2	2	
Resp. 7	2^6	2^6	4	1	1	1^2	2/3	3	5	2^4	2^4	2^4	2	2	2	2

other) are separated by a “|”. Since the response to X can indeed be different depending on whether X is increasing or decreasing, these cells do not represent a conflict but rather the opportunity to consider agreement in both the “X-up” and “X-down” direction. In these cases it was possible to have agreement in one direction but not the other.

The columns in Table 2-6 represent individual influences (arrows) in the group influence diagram, and rows represent individual respondents. Dark green shaded columns indicate agreement on both type and degree of influence; light green shaded columns indicate agreement on type but not degree; gray shaded columns indicate no agreement. Within columns, numbers in green are those that fall into the same (majority) grouping in terms of type of influence (even though degree is different), while codes in pink indicate disagreement about type. Columns outlined in red indicate threshold influences where there was either: (1) a change in type of influence in the climate scenarios compared to current conditions (e.g., from a direct to an inverse relationship), (2) a change in sensitivity (e.g., a change from a proportional to disproportional response, or (3) an indication by multiple participants in their notes or in the group discussions that the influence was likely a threshold relationship (although they did not always know exactly which scenario in which this would occur). In these cases the type and/or degree of influence for the relationship would depend on a threshold, the exact location of which is uncertain.

There were 32 influences in total. Under current conditions, there was agreement on both type and degree of influence for 62% of the influences, agreement on type but not degree for 22% and no agreement for 16%. Under Climate Scenario A, this shifted to 53% of influences with agreement on both type and degree, 28% with agreement on type but not degree and 19% with no agreement. Under Climate Scenario B, influences with agreement continued to decline, with 40.5% for which there was agreement on both type and degree, 40.5% with agreement on type but not degree and 19% with no agreement.

2.3.1.2.2. Thresholds

Relationship E (Nutrient Inputs on Below Ground Biomass) and Relationship EE (Net Accretion on Sediment Deposition/Retention) were identified to be threshold relationships under the climate scenarios. In both of these cases the type of influence changed across the scenarios, with Relationship E changing from direct to inverse under Climate Scenario A, and Relationship EE changing from inverse proportional to direct proportional under Climate Scenario B. The sensitivity for both of these influences did not change across the scenarios.

The threshold of Relationship E is related to the vegetative response to nutrient inputs. An increase in nutrients can increase net below ground peat because it spurs above ground productivity, a portion of which adds to below ground peat. At the same time, nutrients decrease below ground production and increase decomposition. In the long term, the below ground effects of nutrients could outweigh the above ground ones and cause the relationship to change from direct to inverse.

The threshold of Relationship EE is related to the response of sediment deposition and retention to net accretion. A threshold could occur where a given location is under a different inundation regime due to sea level rise, and thus exposed to different tidal velocities and a different deposition regime. Where the marsh is shallow enough, an increase in accretion would decrease net sediment deposition because the water would have already been slowed during inundation and dropped its sediment load. However with a sufficient increase in sea level under climate change, the marsh could now be at a depth where the water would arrive at higher velocities during inundation, still carrying a high sediment load, such that now an increase in accretion would cause water to slow and increase deposition.

Relationship Z (Inundation Regime on Sediment Deposition/Retention) and Relationship BB (Inundation Regime on Below Ground Biomass) were identified to be threshold relationships under current conditions and the climate scenarios. Here the type and sensitivity of the influences did not change across the scenarios; there was no agreement on type or degree of influence in both cases, but this was because the codes were a mixture of direct proportional and inverse proportional, with some participants indicating both codes at once. It emerged through participant discussions that these are threshold relationships for which it is unclear exactly when the tipping points would occur (hence the inability to identify them as a change across scenarios). For both of these influences, the threshold was indicated to be where too much inundation leads from a direct (positive) relationship to a tipping point (inverse relationship) with the response variable. In the case of Relationship Z, an increase in inundation would initially increase transport and deposition of sediment, but at some point too great an increase in inundation could lead to such an increase in erosion as to cause a net decrease in deposition and retention. Similarly for Relationship BB, while increased inundation initially supports productivity of below ground biomass, too great an increase in inundation would lead to low levels of oxygen and “smothering” of below ground biomass.

Relationship AA (Marsh Edge Erosion on Sediment Deposition/Retention) was identified as a threshold relationship under the climate scenarios in discussions. The type and sensitivity of the influence did not change across the scenarios (the relationship had no agreement under current conditions, and was identified as inverse proportional under the climate scenarios). However, it was identified in the later group discussion as an important potential threshold due to the sensitivity of marsh edge erosion to future increases in storm intensity (with a strong seasonal component), especially given sea level rise. The greater influence of storms under the climate scenarios would lead to increasing marsh edge erosion. The resulting effect on sediment deposition and retention would depend on where the sediment was transported—it could either be carried onto the marsh for potential redeposition or lost from the system. The majority of the participants judged that under the climate scenarios, the sediment is more likely to be lost from the system due to the combined effects of sea level rise and changes in inundation and flow regimes. This will serve to greatly increase the inverse effect of marsh edge erosion on sediment deposition and retention. A threshold will occur when erosion losses from the marsh edge exceed the ability of the marsh to capture and retain enough sediment such that accretion no longer sufficiently counteracts losses and the marsh eventually collapses.

One possible reason why some thresholds identified in discussions did not show up in the coding as changes in sensitivity is because participants did not know where the threshold would occur, so they did not want to attach the shift to a particular climate scenario. Alternatively, it may be that there is a threshold that represents a state change that falls within the range of natural variability, so this method was not sensitive enough to identify the threshold.

2.3.1.3. *Influence Sensitivity*

Figure 2-4 shows the sensitivity results using the influence diagram, indicating where there is agreement under current conditions. The typology described in Section 2.2.2.5 was used to code sensitivity, with an additional differentiation within the "no agreement" category. In all "no agreement" cases, there was a mixture of codes for intermediate sensitivity along with low and/or high sensitivity; if at least four participants provided judgments, and there were more high sensitivity judgments than low sensitivity judgments, then the dashed arrow was colored orange to indicate intermediate-to-high sensitivity. Under current conditions, 23 influences with agreement were categorized as intermediate sensitivity. Relationship M (Coastal and Nearshore Erosion on Tidal Exchange) was the only influence categorized as "low sensitivity". For Relationship J (Marsh High Water Level on Coastal and Nearshore Erosion), there was agreement that there is high sensitivity when marsh high water level is increasing and intermediate sensitivity when marsh high water level is decreasing. There was no agreement on sensitivity for six influences. Relationship G (Altered Flows: Tidal Restrictions on Freshwater Flow) was categorized as having no influence.

Figure 2-5 compares the sensitivities as in Figure 2-4, across the three scenarios. Under Climate Scenario A, Relationship J (Marsh High Water Level on Coastal and Nearshore Erosion) continued to show agreement on high sensitivity when marsh high water level is increasing, while agreement on sensitivity was lost when marsh high water level is decreasing. Relationship H Land Cover: Percent Impervious Cover on Freshwater Flow) showed a trend

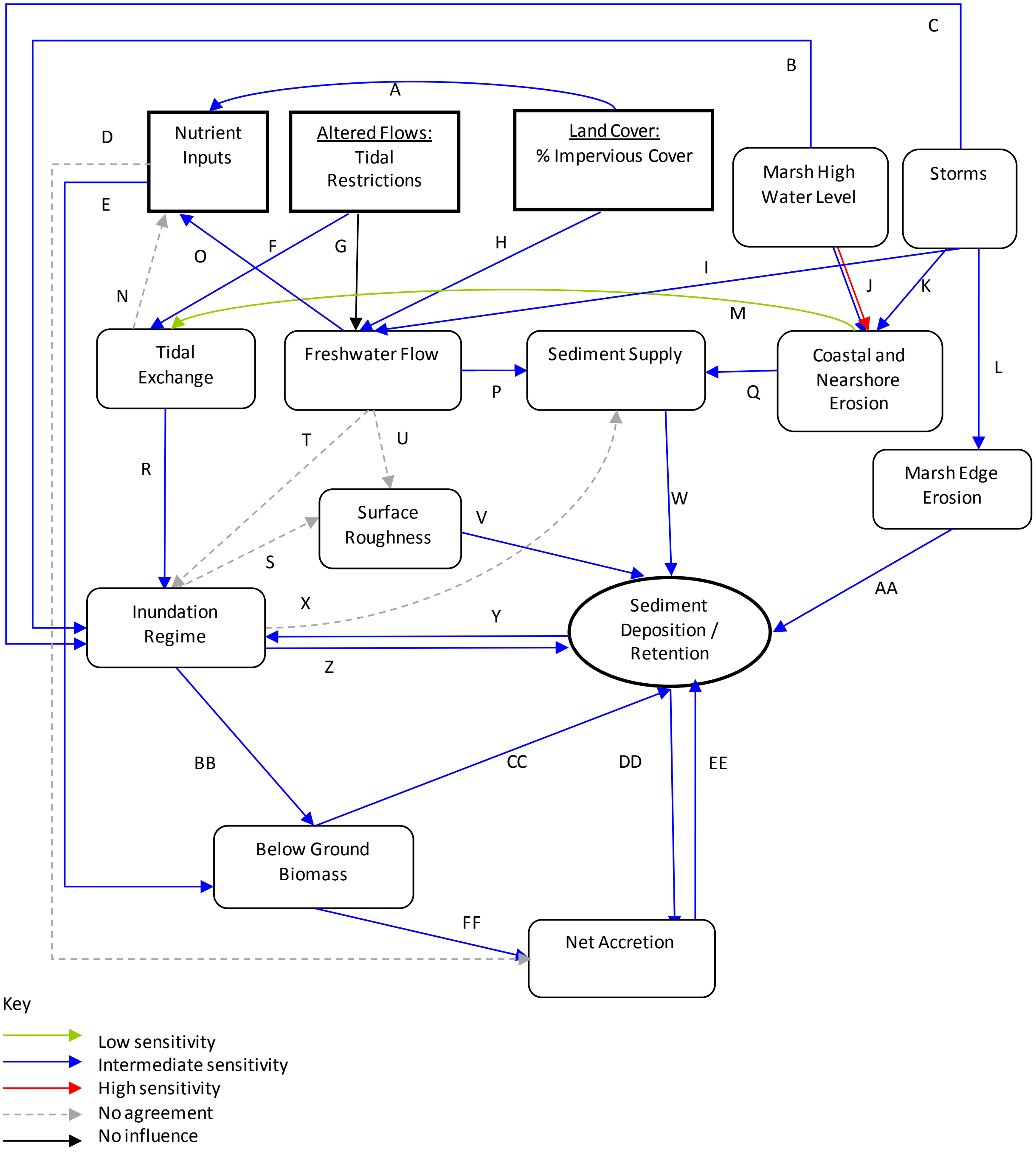


Figure 2-4. Sediment Retention group summary influence diagram of sensitivities under current conditions.

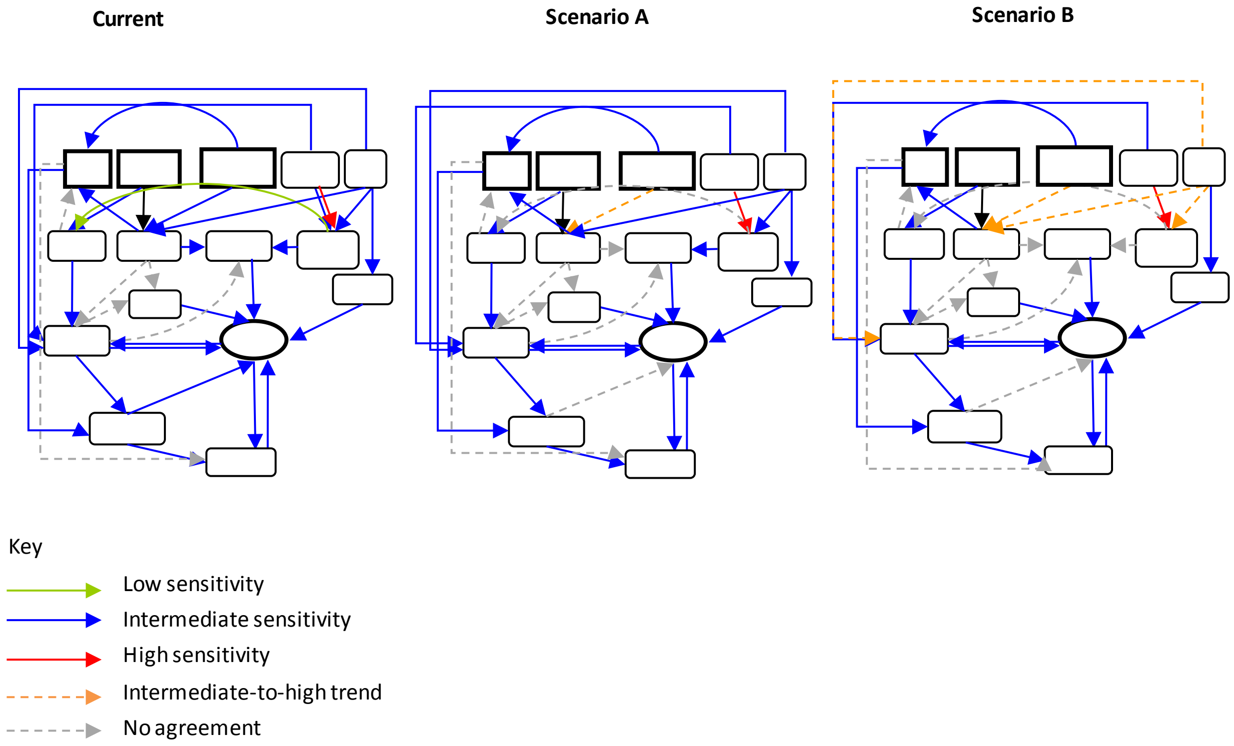


Figure 2-5. Sediment Retention group summary influence diagrams of sensitivities: variance across current conditions and two climate scenarios.

from intermediate (to intermediate-to-high sensitivity (orange arrow). Most of the other influences that were previously characterized as intermediate sensitivity remained the same, with the exception of: Relationship P (Freshwater Flow on Sediment Supply) and Relationship CC (Below Ground Biomass on Sediment Deposition/Retention), for which there no longer was agreement. There was no agreement on sensitivity under the climate scenarios for Relationship Q (Coastal and Nearshore Erosion on Sediment Supply), which had low sensitivity under current conditions.

Under Climate Scenario B, four additional intermediate sensitivity influences dropped below the standard of agreement: Relationships C, I, and K (Storms on Inundation Regime, on Freshwater Flow, and on Coastal and Nearshore Erosion), and Relationship Q (Coastal and Nearshore Erosion on Sediment Supply). However, in the case of Relationships C, I, and K, the lack of agreement was due to a subset of participants indicating a change toward increasing sensitivity (orange arrows). Thus, these influences (along with Relationship J, which remained the same as in Climate Scenario A) are considered intermediate-to-high in sensitivity.

One reason for lack of agreement on changes in sensitivity across scenarios, as well as lack of agreement within scenarios, may have been the degree of variability among participants in their judgements. Overall, there was more variability among participants than across scenarios for any given participant. There were no patterns across participants, such as characterizing only increasing sensitivity. Further description, as well as figures depicting variability in judgments across participants, can be found in Appendix B.

2.3.1.4. *Relative Impact*

Figure 2-6 presents the characterization of relative impacts for current conditions while Figure 2-7 compares the relative impacts across all three scenarios. Under current conditions, a total of 24 influences were identified as having high relative impact. The Sediment Retention group distinguished relative impact of the influences by indicating primary and secondary degrees of impact. Primary impact was indicated for 14 influences, while secondary impact was indicated for 10 influences. Influences of primary impact at the top of the diagram (which are associated with management options) include Relationships B and J (Marsh High Water Level on Inundation Regime and on Coastal and Nearshore Erosion), Relationship E (Nutrient Inputs on Below Ground Biomass), and Relationship F (Altered Flows: Tidal Restrictions on Tidal Exchange).

Under both Climate Scenarios, the influence of Relationship B (Marsh High Water Level on Inundation Regime) was identified as having increasing impact. Relationship E (Nutrient Inputs on Below Ground Biomass) and Relationship V (Surface Roughness on Sediment Deposition/Retention) were identified as having increasing impact under Climate Scenario B. Relationship CC (Below Ground Biomass on Sediment Deposition/Retention) increased from secondary impact under current conditions to primary impact under Climate Scenario A, yet decreased back to secondary impact under Climate Scenario B.

2.3.1.5. *Confidence*

The confidence results shown in Table 2-7 are provided for the Sediment Retention influences for which there was agreement on type. The lack of agreement on confidence for almost half of the judgments is a significant gap, limiting our ability to prioritize around confidence judgments. All of the 12 influences for which there was agreement on confidence across all three scenarios were scored as high evidence and high agreement (HH). Relationship G (Altered Flows: Tidal Restrictions on Freshwater Flow), Relationship Y (Sediment

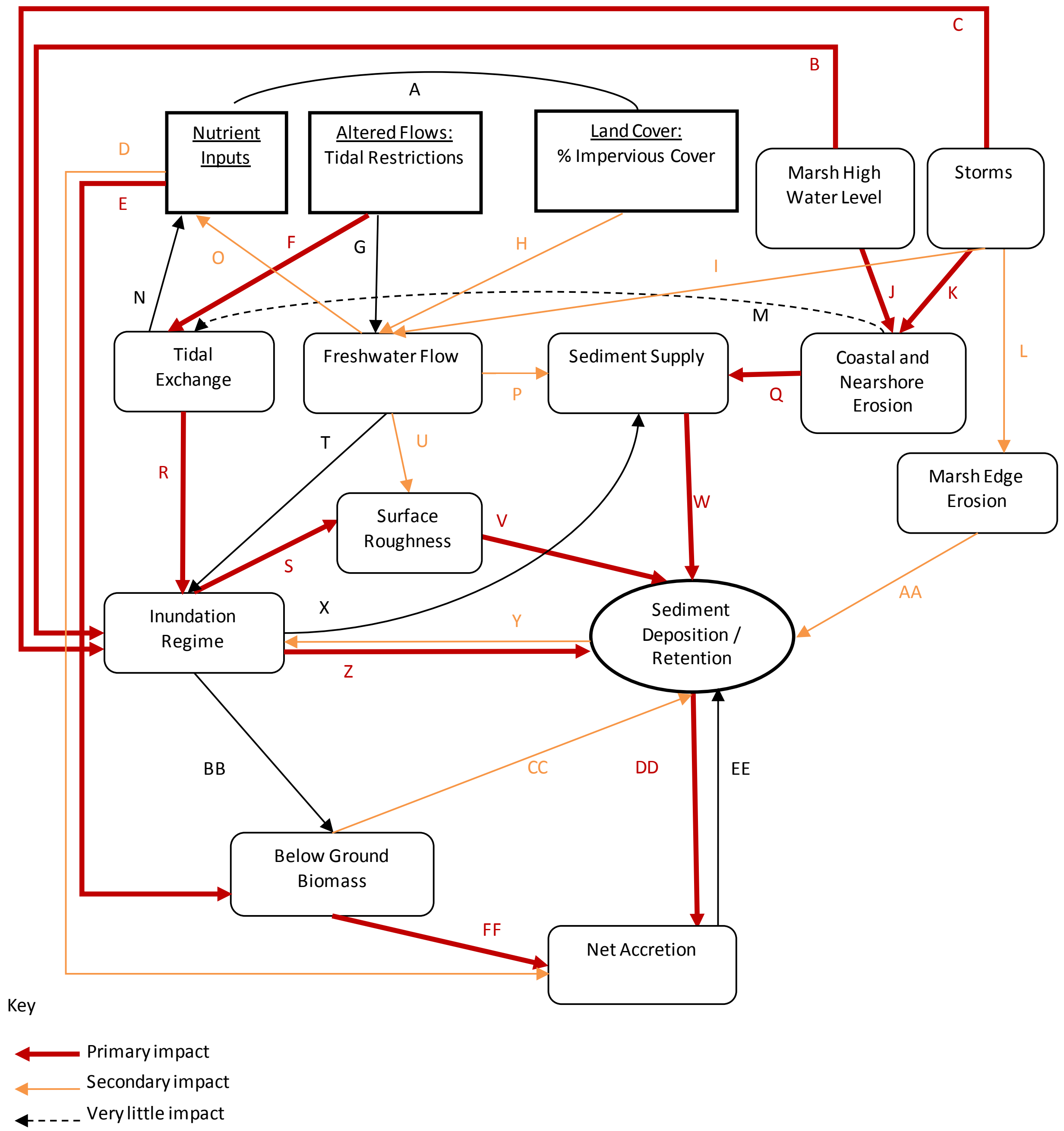


Figure 2-6. Sediment Retention influences indicated as having high *relative impact* under current conditions.

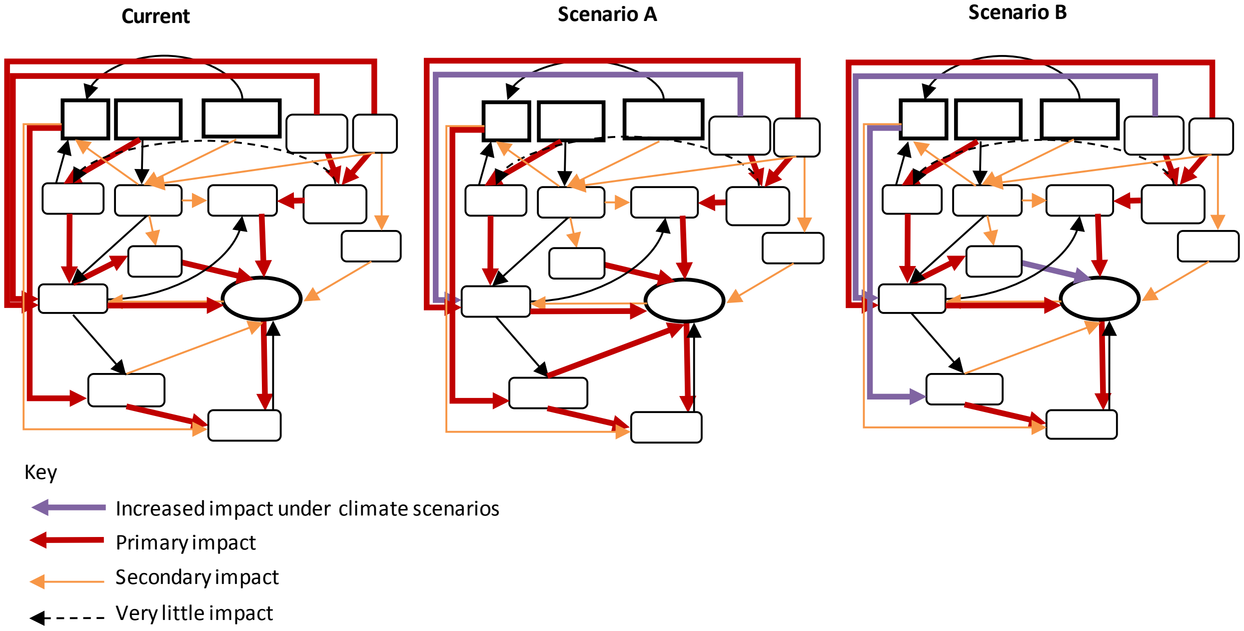


Figure 2-7. Sediment Retention influences indicated as having high *relative impact*: variance across current conditions and two climate scenarios.

Table 2-7. Sediment Retention group confidence for influences with agreement

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**T**	**V**	**W**	**X**	**Y**	**AA**	**CC**	**DD**	**EE**	**FF**
Current	HH	HH	HH	NA	NA	HH	HH	HH	HH	NA	HH	NA	NA	NA	HH	HH	NA	HH	NA	HH	HH	NA	HH	NA	NA	HH	NA	HH
Scenario A	HH	HH	HH	NA	NA	HH	NA	HH	HH	HH	HH	HH	NA	NA	HH	HH	NA	HH	NA	HH	HH	NA	NA	NA	NA	HH	NA	NA
Scenario B	HH	HH	HH	NA	NA	HH	NA	HH	HH	HH	HH	HH	NA	NA	NA	HH	NA	HH	NA	HH	HH	NA	NA	NA	NA	HH	NA	NA

NA = no agreement; HH = high evidence, high agreement; HL = high evidence, low agreement; LH = low evidence, high agreement; LL = low evidence, low agreement.

Deposition/Retention on Inundation Regime), and Relationship FF (Below Ground Biomass on Net Accretion), which were categorized as HH under current conditions, showed declining agreement on confidence under the climate scenarios, with no agreement under Climate Scenarios A and B. Relationship J (Marsh High Water Level on Coastal and Nearshore Erosion), as well as Relationship L (Storms on Marsh Edge Erosion), for which there was no agreement under current conditions, showed increasing agreement under the climate scenarios, with a score of HH under Climate Scenario A and Climate Scenario B. An overall decrease in the total number of HH judgments from current conditions to the climate scenarios and a corresponding increase in the total number of LL judgments show that influences become less well-understood due to less information being available about future climate conditions.

2.3.1.6. *Interacting Influences*

Table 2-8 presents the interactive influences upon which there was agreement for the Sediment Retention group. The interactive influence columns indicate the type of interactive influence and associated number of participants that chose that particular interactive influence type. The confidence columns indicate the confidence judgment and associated number of participants that chose that particular confidence score.

Under current conditions, there were two interactive influences for which there was agreement among participants in the Sediment Retention group. For both of these interactive influences, Synergy was the type of influence chosen. These interactions included Relationship B with C (Marsh High Water Level on Inundation Regime with Storms), and Relationship V with W (Surface Roughness on Sediment Deposition/Retention with Sediment Supply). There was only agreement on the confidence for the interactive influence of Relationship B with C, which was scored HH.

Under both Climate Scenario A and Climate Scenario B, there was one of the previous two synergistic interactive influences for which there was agreement on synergy as the type of interactive influence (Relationship B with C). This interactive influence remained as HH under the climate scenarios. There were two new interactive influences for which there was agreement under the climate scenarios, both of which were scored as Synergy. These interactions included Relationship H with I (Land Cover: Percent Impervious Cover on Freshwater Flow with Storms), and Relationship W with V (Sediment Supply on Sediment Deposition/Retention with Surface Roughness). Confidence on both of these interactive influences was scored as HH under Climate Scenario A, though there was no agreement on confidence under Climate Scenario B for Relationship H with I.

Table 2-8. Sediment Retention group interactive influences with agreement under current conditions and Climate Scenarios A and B

Interaction	Variable X	on	Variable Y	with	Variable Z	Current		Climate A		Climate B	
						Interactive influence	**Confidence**	**Interactive influence**	**Confidence**	**Interactive influence**	**Confidence**
B+C	Marsh High Water Level	on	Inundation Regime	with	Storms	Synergy (4)	HH	Synergy (6)	HH	Synergy (6)	HH
H+I	Land Cover: Percent Impervious Cover	on	Freshwater Flow	with	Storms	NA	NA	Synergy (3)	HH	Synergy (3)	NA
V+W	Surface Roughness	on	Sediment Deposition/ Retention	with	Sediment Supply	Synergy (3)	NA	NA	NA	NA	NA
W+V	Sediment Supply	on	Sediment Deposition/ Retention	with	Surface Roughness	NA	NA	Synergy (3)	HH	Synergy (3)	HH

NA = no agreement; HH = high evidence, high agreement; HL = high evidence, low agreement; LH = low evidence, high agreement; LL = low evidence, low agreement; () = number of respondents.

There was no agreement on type of interactive influence under the climate scenarios for the interaction of Relationship V with W (Surface Roughness on Sediment Deposition/Retention with Sediment Supply), which was identified as Synergy under current conditions. Meanwhile, the Relationship W with V (Sediment Supply on Sediment Deposition/Retention with Surface Roughness) was identified as Synergy under the climate scenarios. The change from "V with W" to "W with V" distinguishes between the effect of Surface Roughness on the endpoint increasing with an increase in Sediment Supply, and the effect of Sediment Supply on the endpoint increasing with an increase in Surface Roughness. It is unclear whether participants intended to highlight this difference, or if there was confusion about the definition during the exercise. Both interactions may be important, but there may not have been time to explore interacting influence pairs separately across scenarios.

One additional interaction, Relationship J with K (Marsh High Water Level on Coastal and Nearshore Erosion with Storms), was only identified by two participants (as a Synergy) in the coding. However, this same interplay was brought up during group discussions as an interaction of potential importance under climate change, implying that further investigation into the relationship of these influences may be warranted.

The limited number of interacting influences for which there was agreement was primarily due to not having many influences with enough participants characterizing the same interacting influences. Of the 48 combinations of influences with interactions characterized by participants, only nine could be considered for agreement with at least three participants making a judgment; less than half of those had three participants in agreement.

2.3.2. Community Interactions

2.3.2.1. *Group Influence Diagram*

Figure 2-8 shows the group diagram developed by the Community Interactions group. Variable definitions that were developed by the participants during the construction of the diagram are found in Table 2-9. Three variables directly influence the endpoint of Saltmarsh Sharp-Tailed Sparrow Nesting Habitat: the Ratio of Low Marsh (*Spartina alterniflora*) to High Marsh (*Spartina patens*) species, Inundation Regime, and Marsh Elevation. The Ratio of Native High Marsh to invasive *Phragmites* is a key factor influencing the endpoint through the Ratio of Low Marsh to High Marsh as well as Marsh Elevation. The middle level in the diagram includes Salinity, Sedimentation, Nitrogen, Above Ground Plant Biomass, and Below Ground Plant Biomass. These variables and the ones that directly influence the endpoint are all highly interconnected, with Inundation Regime, Above Ground Biomass and both ratio variables serving as hubs.

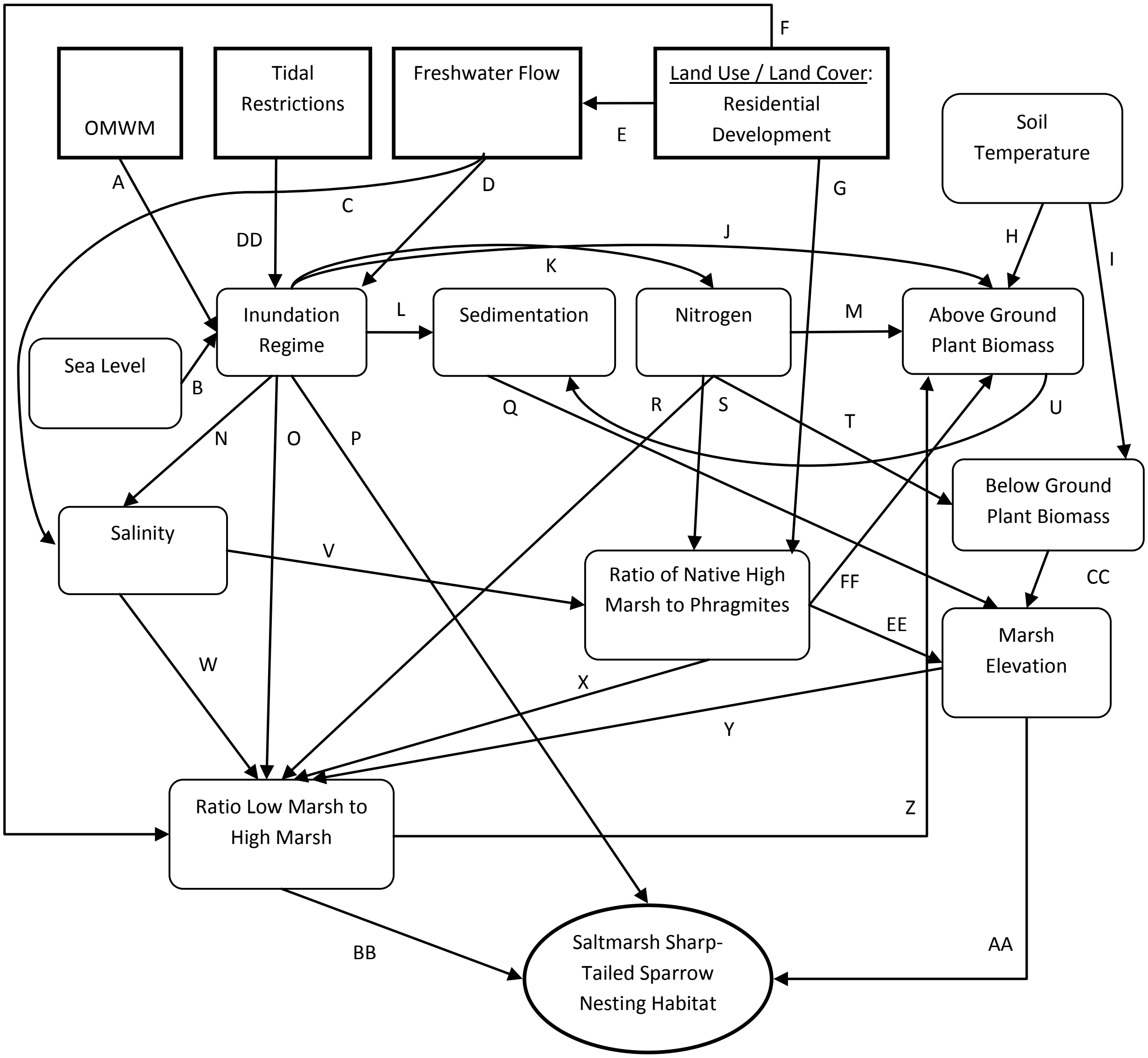


Figure 2-8. Community Interactions group influence diagram.

Table 2-9. Community Interactions variable definitions

Variable	Definition agreed upon by group
Open Marsh Water Management (OMWM)	Acreage of projects creating and connecting ponds and pools
Sea Level	Water height (mm) at mean lower low water
Freshwater Flow	[1] cfs at gauging stations on Ipswich and Parker Rivers, trends over time [EPA] Rate of freshwater inflow to the estuary from the watershed
Land Use / Land Cover: Residential Development	[1] (relative area of upland cleared *0.5) + (relative area of impervious surface) [2] Percent border developed and proximity (km) from sensitive habitats (i.e., marsh) [3] Percent watershed developed (all human made structures and landscapes) [4] Percent residential (among others) [5] Lawn/asphalt in shoreland zone
Soil Temperature	Soil temperature in °C or °F
Tidal Restrictions	Any restriction to tidal inundation into the marshes (e.g., road crossings or any other barrier to inflow)
Inundation Regime	Percent time high marsh under water during April−October
Sedimentation	Average concentration of suspended sediment in the water column (mg/L)
Nitrogen	[1] Unit N/unit area/year (g $N/m^2/yr$) [2] Total inorganic Nitrogen inputs from uplands [3] kg/ha/yr to Plum Island Sound measured from permanent Long Term Ecological Research Network sampling stations
Above Ground Plant Biomass	[1] Biomass accumulation rate [EPA] Total mass of plant material
Salinity	Soil salinity (ppt)
Below Ground Plant Biomass	Percent organic matter
Ratio of Native High Marsh to *Phragmites*	Percent extent (m) of high marsh vegetation to *Phragmites* cover
Marsh Elevation	Height above mean lower low water
Ratio Low Marsh to High Marsh	[1] Percent extent (m) of low marsh vegetation to high marsh vegetation [2] Percent cover, species composition/abundance
Saltmarsh Sharp-Tailed Sparrow Nesting Habitat	Percent extent of habitat as proportion of total marsh extent, or total area (m^2) available as habitat

The management and stressor variables include: Tidal Restrictions, Open Marsh Water Management (OMWM), Freshwater Flow, and Land Use/Land Cover: Residential Development. OMWM is a mosquito control technique that involves ponding and ditching marshes in order to restore hydrologic conditions to improve fish habitat and thus increase mosquito predation. Removing tidal restrictions, by increasing the size or lowering the opening in the crossing has been one of MBP's management options that restores the inundation regime of the upstream marsh and improves freshwater flow through the restriction to the benefit of the downstream marsh. Soil Temperature and Sea Level are intermediate type variables that could be considered both stressor variables and system variables and are less clearly connected to management-related variables.

2.3.2.2. *Influence Types and Degrees*

2.3.2.2.1. Agreement

Table 2-10 presents the results for the Community Interactions group. As in Table 2-6, the columns in Table 2-10 represent individual influences (arrows) in the group influence diagram, and rows represent individual respondents. Dark green shaded columns indicate agreement on both type and degree of influence; light green shaded columns indicate agreement on type but not degree; gray shaded columns indicate no agreement. Within columns, numbers in green are those that fall into the same (majority) grouping in terms of type of influence (even though degree is different), while codes in pink indicate disagreement about type. For further explanation of table details, see Section 2.3.1.2.

There were 32 influences in total. The participants agreed on the type and degree of influence for slightly fewer of the total number of influences than the Sediment Retention group did. Under current conditions, there was agreement on both type and degree for 56% of the influences, agreement on type but not degree for 25% and no agreement for 19%. Under Climate Scenario A, the number of influences with agreement on both type and degree dropped 47%, the number with agreement on type but not degree remained at 25% and the number with no agreement rose to 28%. Under Climate Scenario B, the number of influences for which there was agreement on both type and degree was 41%, those with agreement on type but not degree was 31% and those with no agreement was 28%.

Compared to the results for the Sediment Retention group, the larger number of influences for which there was no agreement under all scenarios leaves more of a gap in understanding of the type or degree of influence for these relationships. It is difficult to differentiate between lack of response due to insufficient time and disinclination to answer due to lack of knowledge about the influence, however occasionally participants noted if a particular influence was not within their realm of expertise.

Table 2-10. Community Interactions group influence judgments. Columns A−FF represent individual influences (arrows) in the influence diagram and rows represent individual respondents: dark green = agreement on influence type and degree, light green = agreement on type but not degree, gray = no agreement; within columns, green numbers = same (majority) grouping of type (though degree may be different), pink numbers = disagreement about type, red outline = threshold response

Current	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Resp. 1	6	2/3	4	2/3	2/3	6	6	6/11	7|3	6^9	2/3	2/3	2/3	9	2/3	7
Resp. 2	2	2	9	8	2	8	9	2	7	4	1	2	6	8^9	8	9
Resp. 3	2|5	2	9	8	2	2	4	9	4	2	2	2	2	2	2	4
Resp. 4	2	2	4	8	2	8	8	1^2	1	7	2	2	2	2^4	2	7
Resp. 5	2/3	2	4/5		2/3		4/5						2/3		2/3	4/5
Resp. 6	2	2	4	2	1	1	4	6	1	4^6	2	2/3	2	2/3	2	4
Resp. 7			4/5	8|12	2	2/3	2/3	4/5	4/5	2/3	2/3	2/3	2/3	2/3	2/3	7
Climate A	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Resp. 1	6	2/3	4	2/3	2/3	6	6	6/11	3|7	6^9	2/3	2/3	2/3	9	2/3	7
Resp. 2	2^6	6	9	8	2	8	9	2		4	2	2	6	8^9	2	4
Resp. 3		2	9	8	2	6	7	9	4	2	2	2	6	2	2	4
Resp. 4	9	2^6	4	0^8	2	8	8	1	2	2^7	2	2	2	2^4	2	7
Resp. 5	2/3	2	4/5		2/3		4/5						2/3		2/3	4/5
Resp. 6	2	2	4	2	4	1	4	2	1	2^4	2^4	2	2	2^4	2	4
Resp. 7		7|11	4/5	8|12	2	2/3	2/3	4/5	4/5	2/3	2/3	2/3	2/3	2/3	2/3	7
Climate B	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Resp. 1	6	2/3	4	2/3	2/3	6	6	7	7	6^9	2/3	2/3	2/3	9	2/3	7
Resp. 2	8	8	9	8	2	8	9	3		4		2	6	8^9	2	4
Resp. 3		2	9	8	2	6	7	9	4	7	9		6	2	6	4
Resp. 4	9	2^6	4	8	2^6	8	2	1	1	7	9	2^8	2	2^4	2^9	7
Resp. 5	2/3	2	4/5		2/3		4/5						2/3		2/3	4/5
Resp. 6	8	2	4	2	4	1	4	3	1	4	2^4	2^8	2	2^4	2	4
Resp. 7		7|11	4/5	8|12	2	2/3	2/3	4/5	4/5	4	2/3	2/3	2/3	2/3	2/3	7

Table 2-10. Community Interactions group influence judgments. Columns A−FF represent individual influences (arrows) in the influence diagram and rows represent individual respondents: dark green = agreement on influence type and degree, light green = agreement on type but not degree, gray = no agreement; within columns, green numbers = same (majority) grouping of type (though degree may be different), pink numbers = disagreement about type, red outline = threshold response (continued)

Current	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF
Resp. 1	2	2/3	4/5	7	2	2	0	0	10	6/11	11	2/3	2/3	5	4	4
Resp. 2	2	1	3	8	2	12	2|12	2	4	8	3	3	8	2/3	12	
Resp. 3	2	2	4	2^4	2	2	2	4	4	2	2	4	2/3	2|5	12	4/5
Resp. 4	2	2	4	4	8	3	0	0	4	8	8	7	0	7^8	12	
Resp. 5	2/3		4/5	4/5	2/3	2/3					2/3	4/5	2/3	4/5	2/3	
Resp. 6	2	1	4	1	2	2	0^4	0	5	8	6	12	2	2|5	12	2
Resp. 7	2/3	2/3	2/3	4/5	2/3	2/3	1			2/3	7|11	4/5	2/3	7	5	4/5
Climate A	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Y**	**Z**	**AA**	**BB**	**CC**	**DD**	**EE**	**FF**
Resp. 1	2	2/3	4/5	7	2	2	0	0	10	6/11	11	2/3	2/3	5	4	4
Resp. 2	2		4	8	2	2|12	2	2/3	4	8	2/3	3	8	2/3	12	5
Resp. 3	8	2	4	2^4	2	8	2			2			8			
Resp. 4	2	8	4^9	9	8	3	0	13	4	0^8	8	7	8	7^8	12	3
Resp. 5	2/3		4/5	4/5	2/3	2/3					2/3	2/3	2/3	4/5	2/3	
Resp. 6	2	2	4	1	2	2	0	0	5	8	6	4	2	2|5	4	2^4
Resp. 7	2/3	2/3	2/3	4/5	2/3	2/3	1			2/3	7|11	4/5	2/3	7	4	4/5
Climate B	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Y**	**Z**	**AA**	**BB**	**CC**	**DD**	**EE**	**FF**
Resp. 1	2	2/3	4/5	7	2	6	0	0	10	6/11	11	2/3	2/3	5	4	4
Resp. 2	2		4	8	1	1	1		4	8	2/3	3	8	2/3	12	5
Resp. 3	8	7	7	2^4	1	8	2			8			8			
Resp. 4	2	2	4^9	9	2^8	3^11	0	13	4	1	8	1	8	8	12	3
Resp. 5	2/3		4/5	4/5	2/3	2/3					2/3	2/3	2/3	4/5	2/3	
Resp. 6	2|5	2	4	1	2	2	0	0	5	4	2	4	2	2	4	2^4
Resp. 7	2/3	2/3	2/3	4/5	2/3	2/3	1			2/3	11	4/5	2/3	7	4	4/5

2.3.2.2.2. Thresholds

Two relationships were identified as threshold relationships under the climate scenarios, based on the coding scheme, notes and discussions. These were: Relationship J (Inundation Regime on Above Ground Plant Biomass) and Relationship EE (Ratio of Native High Marsh to *Phragmites* on Marsh Elevation). There was no agreement on type or degree of influence for Relationship J under current conditions and Climate Scenario A; however, this was due to the participants recording a mixture of direct and inverse codes and accompanying notes indicating agreement that a threshold response would be expected at some point that is not currently possible to pinpoint. There was agreement on type (inverse) under Climate Scenario B, as a majority of participants agreed that by now the threshold would have likely been passed. The nature of the threshold relationship involves a tipping point in which inundation regime (percent time that high marsh is under water during April−October) at first has a positive effect on above ground plant biomass, but with a sufficient increase would trigger an abrupt decrease in above ground biomass. According to Morris et al. (2002), inundation of sufficient duration is beneficial in that it prevents soil salinity from reaching levels that inhibit growth. However, with sea level rise, inundation frequency and duration is expected to reach levels that cause increased hypoxia and result in marsh die-back (i.e., marsh drowning).

Relationship EE was identified as a threshold relationship because of changes in sensitivity under the climate scenarios. The type of sensitivity for this influence changed from low sensitivity under current conditions to intermediate sensitivity under the climate scenarios. Under current conditions, Relationship EE was identified as an inverse disproportional weak influence; a decrease in the Ratio of Native High Marsh to *Phragmites* would lead to a modest increase in marsh elevation because *Phragmites* is more effective at trapping sediment. Under the climate scenarios, Relationship EE was identified as an inverse influence, with no agreement on degree (due to a mixture of codes moving from an inverse weak relationship toward a more proportional one); here, rising sea levels were identified as the cause of the increasing sensitivity, as *Phragmites* would be better equipped to migrate landward to higher elevations while continuing to more effectively trap sediment in place.

One additional influence, Relationship P (Inundation Regime on Saltmarsh Sharp-Tailed Sparrow Nesting Habitat) was not coded in the exercise as a threshold occurring across the climate scenarios, but was discussed as a unique category of threshold that operates on a shorter time scale. This is an influence that can change dramatically with only slight changes in conditions. Availability of Saltmarsh Sharp-Tailed Sparrow nesting habitat is highly dependent on the timing and amount of inundation, even under current conditions, where nesting habitat can be abruptly flooded out if an even slightly amplified inundation event coincides with the critical nesting period. This phenomenon will become increasingly important as increases in sea level and other factors lead to increased frequency of such flooding events in the future.

2.3.2.3. *Influence Sensitivity*

Figure 2-9 shows the sensitivity results using the influence diagram, indicating where there is agreement under current conditions. The typology described in Section 2.2.2.5 was used to code sensitivity, with an additional differentiation within the “no agreement” category. In all “no agreement” cases, there was a mixture of codes for intermediate sensitivity along with low and/or high sensitivity; if at least four participants provided judgments, and there were more high sensitivity judgments than low sensitivity judgments, then the dashed arrow was colored orange to indicate intermediate-to-high sensitivity. Under current conditions, 21 influences with agreement were categorized as intermediate sensitivity. Two influences were categorized as low sensitivity: Relationship D (Freshwater Flow on Inundation Regime), and Relationship EE (Ratio of Native High Marsh to *Phragmites* on Marsh Elevation). There was no agreement on sensitivity for nine influences; however, five of these influences are indicated in orange due to a combination of intermediate and high sensitivity codes. There were no instances of agreement on influences with high sensitivity.

Figure 2-10 compares the sensitivities as in Figure 2-9, across the three scenarios. Under Climate Scenario A, 20 influences with agreement were categorized as intermediate sensitivity. One influence changed from low sensitivity under current conditions to intermediate sensitivity under the climate scenarios (Relationship EE). Relationship D was the only influence categorized as low sensitivity. No influences were categorized as high sensitivity. The number of influences with no agreement increased to 11; however, three of these are indicated in orange due to a combination of intermediate and high categorizations of sensitivity. Such decreases in agreement highlight a trend of increasing sensitivity for some participants, but not enough to shift to agreement on a new category. It could be indicative of either disagreement about at what point such a shift would occur or of differing assumptions about what falls outside the current range of variability, which was left up to each participant to decide based on their own knowledge and intuition.

Under Climate Scenario B, 17 influences with agreement were categorized as intermediate sensitivity. As with Climate Scenario A, only one influence was categorized as low sensitivity. The number of influences with no agreement increased further, to 14; however, four of those are indicated as orange due to a combination of intermediate and high sensitivity. No influences were categorized as high sensitivity.

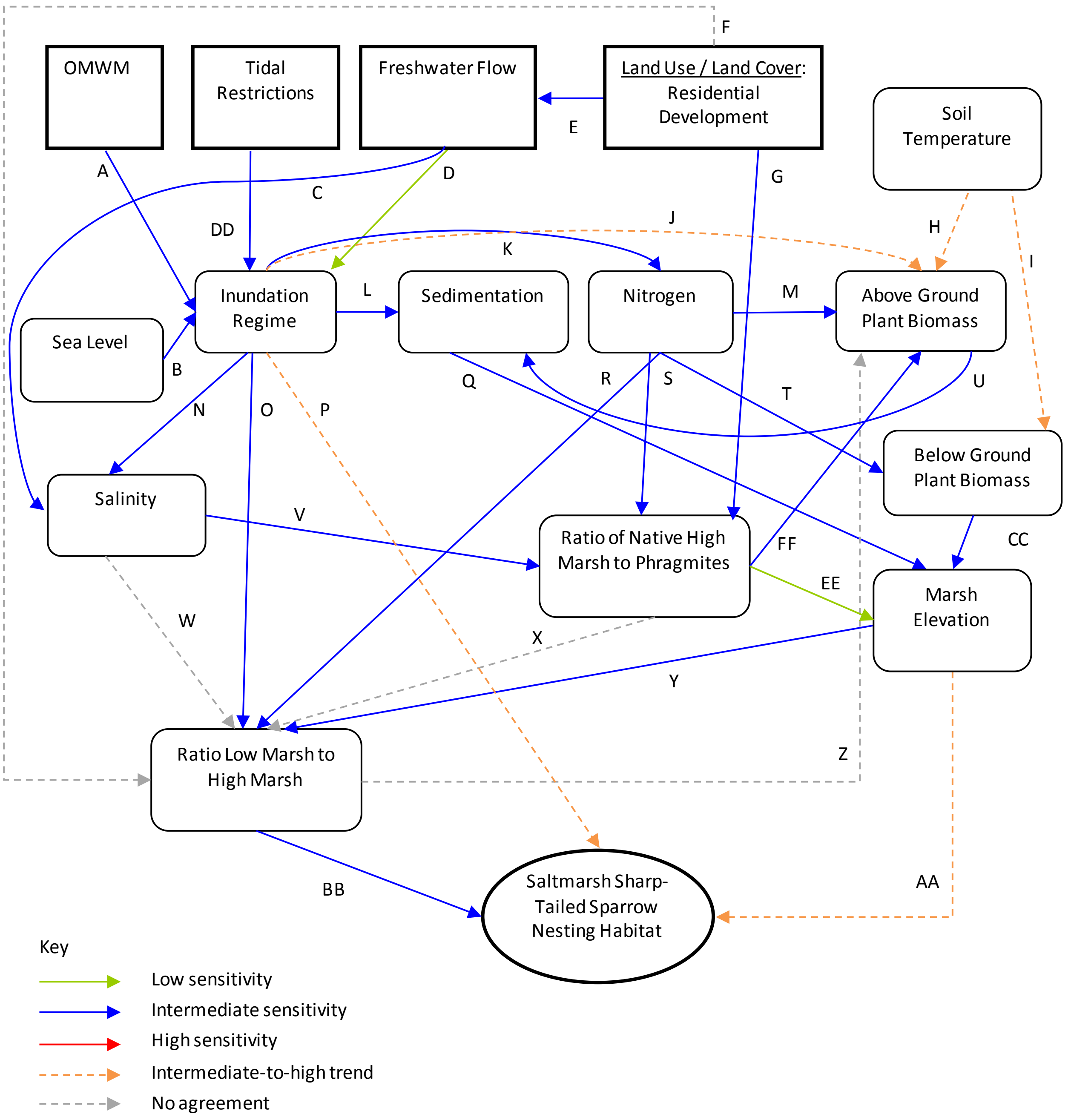


Figure 2-9. Community Interactions group summary influence diagram of sensitivities under current conditions.

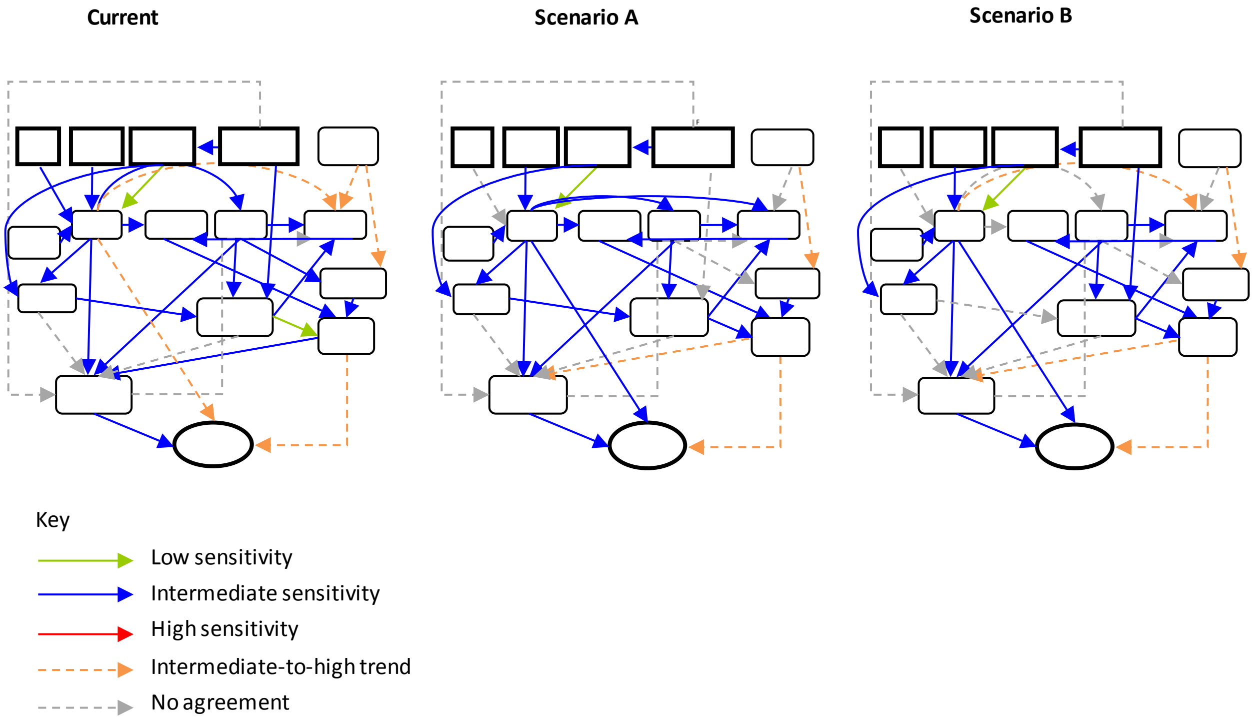


Figure 2-10. Community Interactions group summary influence diagrams of sensitivities: variance across current conditions and two climate scenarios.

One reason for lack of agreement on changes in sensitivity across scenarios, as well as lack of agreement within scenarios, may have been the degree of variability among participants in their judgements. Overall, there was more variability among participants than across scenarios for any given participant. The majority of changes in sensitivity type across the climate scenarios are of increasing sensitivity. Further description, as well as figures depicting variability in judgments across participants, can be found in Appendix B.

2.3.2.4. *Relative Impact*

Figure 2-11 presents the characterization of relative impact between current and future climate scenarios (the group's discussion did not differentiate between the two future climate scenarios). This group distinguished among the influences by indicating primary impact, interactive influences with high relative impact, and influences that had some agreement but no consensus on relative impact. Under current conditions, nine influences were indicated as having high relative impact, based on the discussion. Influences of primary impact at the top of the diagram (which are associated with management options) include Relationship A (OMWM

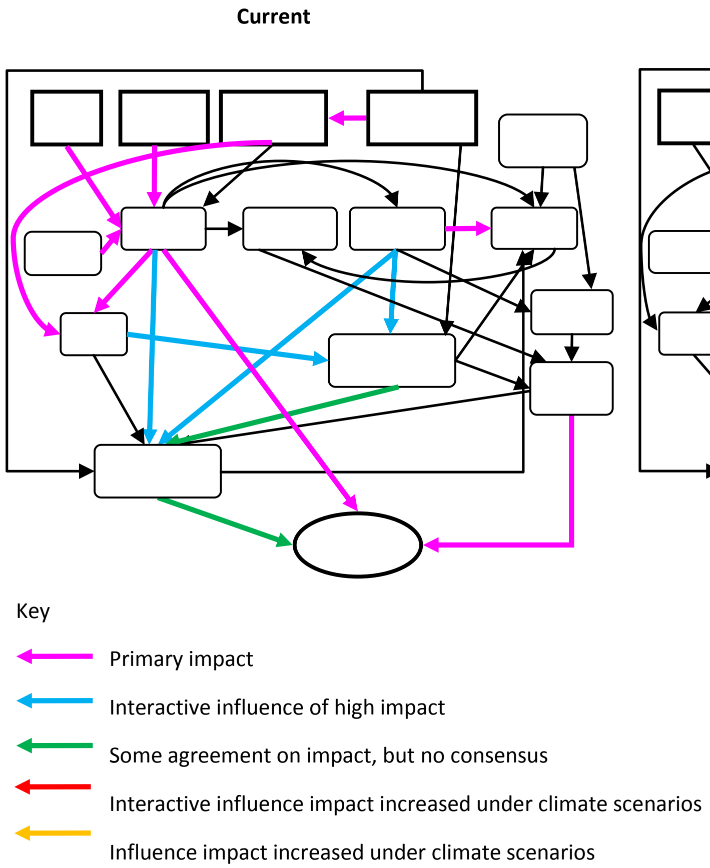


Figure 2-11. Community Interactions influences indicated as having high *relative impact* under current conditions and the climate scenarios.

on Inundation Regime), Relationship C (Freshwater Flow on Salinity), Relationship E (Land Use/Land Cover: Residential Development on Freshwater Flow), and Relationship DD (Tidal Restrictions on Inundation Regime). Two influences were indicated as having some agreement on high relative impact: Relationship X (the Ratio of Native High Marsh to *Phragmites* on the Ratio of Low Marsh to High Marsh), as well as Relationship BB (the Ratio of Low Marsh to High Marsh on Saltmarsh Sharp-Tailed Sparrow Nesting Habitat). Two pairs of interactive influences were indicated as having high relative impact: Relationship O with R (Inundation Regime on the Ratio of Low Marsh to High Marsh with Nitrogen), as well as Relationship S with V (Nitrogen on the Ratio of Native High Marsh to *Phragmites* with Salinity).

Under the climate scenarios (see Figure 2-11) it is assumed that the same relationships are still of high impact, and only additions or changes in relative impact are shown in the second panel. Three influences were indicated as increasing in relative impact under climate change conditions for the Community Interactions group: Relationship L (Inundation Regime on

Sedimentation), Relationship O (Inundation Regime on the Ratio of Low Marsh to High Marsh), and Relationship V (Salinity on the Ratio of Native High Marsh to *Phragmites*). The interactive influence of Relationship H with J (Soil Temperature on Above Ground Plant Biomass with Inundation Regime) was indicated as having increasing relative impact under the climate scenarios.

2.3.2.5. *Confidence*

The confidence results shown in Table 2-11 are provided for the Community Interactions influences for which there was agreement on type. The lack of agreement on confidence for almost half of the judgments is a major gap, limiting our ability to prioritize around confidence judgments. Three of the four influences for which there was agreement on confidence across all scenarios were scored as HH. Relationship AA (Marsh Elevation on Saltmarsh Sharp-Tailed Sparrow Nesting Habitat) was scored as LH across all scenarios. The HH type of confidence was the most common judgment. The dominant pattern on confidence across the climate scenarios was a decrease in the number of influences on which there was agreement. An overall decrease in the total number of HH judgments from current conditions to the climate scenarios and a corresponding increase in the total number of LL judgments show that influences become less well-understood due to less information being available about future climate conditions.

2.3.2.6. *Interacting Influences*

Under all scenarios, the interaction of Relationship A with B (OMWM on Inundation Regime with Sea Level) was the only interactive influence with agreement among participants. Synergy was the type of influence chosen; this means that the effect of open marsh water management (which creates and connects ponds and pools) on inundation regime is intensified with sea level rise. There was no agreement on the confidence for this interactive influence.

The lack of agreement on any other potential interacting influences was primarily due to not having many instances of enough participants characterizing the same interactions. Of the 25 combinations of influences with interactions characterized, only two could be considered for agreement with at least three participants making a judgment; only one of those had three participants in agreement. One of the interactions that was only identified by one participant in the coding, Relationship H with J (Soil Temperature with Inundation Regime on Above Ground Plant Biomass, Competition) was brought up in the group discussion as an interplay of increasing relative impact under climate change (see Figure 2-9), indicating that further investigation of this interaction may be desirable.

Table 2-11. Community Interactions group confidence for influences with agreement

	A	**B**	**C**	**D**	**E**	**F**	**G**	**I**	**J**	**K**	**L**	**M**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**	**Y**	**Z**	**AA**	**BB**	**CC**	**DD**	**EE**	**FF**
Current	NA	HH	HH	NA	HH	NA	NA	NA	NA	HH	HH	HH	HH	HH	HH	NA	NA	NA	HH	HH	HH	NA	LH	LH	HH	HH	HH	HH
Scenario A	NA	NA	HH	NA	HH	NA	NA	NA	NA	NA	HH	HH	NA	NA	HH	NA	NA	NA	HH	NA	NA	NA	LH	NA	NA	NA	NA	NA
Scenario B	NA	NA	HH	NA	HH	NA	NA	NA	NA	NA	NA	HH	LH	NA	NA	NA	NA	NA	NA	NA	NA	NA	LH	NA	NA	NA	NA	NA

NA = no agreement; HH = high evidence, high agreement; HL = high evidence, low agreement; LH = low evidence, high agreement; LL = low evidence, low agreement.

Finally, two additional interactions that were not coded by individual participants were identified by the group as interactions of high relative impact under current conditions (see Figure 2-9). These were the effects of: (1) nitrogen with inundation regime on ratio of low marsh to high marsh; and (2) nitrogen with salinity on ratio of high marsh to *Phragmites*. The first interaction is a synergy between inundation regime and nitrogen. Low marsh plants are better at dealing with inundation than high marsh plants due to their greater tolerance of high salinity and low soil oxygen content; and the high marsh species dominate the upper zone due to their superior competitive ability in obtaining below-ground nutrients (Bertness and Pennings, 2002). Under climate change, nitrogen may no longer be limiting due to greater nutrient runoff, while greater inundation of saline water is also expected; together these factors will synergistically favor low marsh species. The second interaction—the effect of nitrogen with salinity on ratio of high marsh to *Phragmites*—is a competition, where increased nitrogen has a positive impact on *Phragmites* while increased salinity has a negative effect.

2.4. DISCUSSION OF ADAPTATION STRATEGIES

With a structure for considering management priorities provided by MBP, the workshop participants discussed the implications of the exercise results for management. Workshop observers also participated in the discussion. Table 2-12 lists adaptation strategies that emerged during the group discussions. The experts discussed a variety of general adaptation strategies as well as some specific adaptation activities that would be responsive to key potential climate-related changes identified through their judgments. The strategies fall into several broad categories including Restoration and Conservation, Reducing Nonclimate Stressors, and Monitoring and Planning. While some of the strategies were specifically generated for management of one or the other ecosystem process, many are applicable to both Sediment Retention and Community Interactions and to salt marsh ecosystem processes not included in the workshop.

2.4.1. Restoration and Conservation

Restoration and conservation together make a powerful adaptation strategy because they contribute to increased resilience of the overall system. General restoration guidelines that were discussed include restoring the “habitat mosaic” in order to provide a connected landscape that maintains biodiversity in case of disturbance of individual pieces of the mosaic. Conservation is

Table 2-12. Adaptation strategies and associated top pathways for management (see Figures 3-3 and 3-4 for pathways)

Adaptation strategies	Pathways
Conduct “multihabitat restoration” (i.e., restore the “habitat mosaic”) with a priority on habitats with the highest values	CG
Recognize and take advantage of the ability of marshes to “restore” themselves under the right conditions	SG, CG, CB, CP
Monitor the composition of the inorganic sediments in the marsh, as well as the structure of the peat	SB, SP
Measure local maximum growth rates to determine the degree of sea level rise that vegetation can withstand, and manage around that threshold/target level	CG, CB, SB
Monitor the line between high and low marsh areas to determine how the marshes are holding up against sea level rise	SG, CG, CP
Identify, acquire and/or protect potential areas where marsh can grow and expand, and remove barriers to marsh migration	SG, CG, CB
Upgrade sewage treatment plants (e.g., tertiary treatment) and combined sewer overflow systems to reduce the flow of excess nutrients into the marsh	SB, CG
Improve stormwater management to reduce nonpoint source nutrient inputs into the marsh	SB, CG
Promote more absorbent land cover and “rain catchers” to prevent additional runoff	SB, CG
Control the hydrodynamic regime (including through channel creation/ditch modification) to favor certain vegetation types	CG, CP
Restore tidal connections (e.g., remove tidal restrictions) in the near term, with awareness that negative effects could arise under climate change	SG, CB
Control invasive species (e.g., *Phragmites*)	CG
Conduct activities to control erosion, (e.g., create “no wake zones” to reduce marsh edge erosion from boat wakes)	SP
Establish oyster reefs for habitat, filtering of pollutants and erosion control.	SP, CG
Work with programs responsible for protecting coastal infrastructure to ensure that marsh protection is included in management plans (i.e., take advantage of capacity of marshes to buffer infrastructure against coastal storms and sea level rise)	SP, CG
Conduct education and outreach to promote good practices for marsh management	SB, SP, CG
Avoid potential maladaptations (e.g., placement of dikes that result in an unintentional magnification of erosion effects on adjacent salt marshes)	SP
Where change is unavoidable, manage and sustain new habitats that are created when others are wiped out (e.g., when mudflats replace low marsh areas)	SG, SP, CG

SG = Sediment Retention Green pathway; SB = Sediment Retention Blue pathway; SP = Sediment Retention Purple pathway; CG = Community Interactions Green pathway; CB = Community Interactions Blue pathway; CP = Community Interactions Purple pathway.

implicit in consideration of where to prioritize restoring habitats within the existing landscape continuum of healthy to degraded habitats, with a need to conserve the habitats that are adjacent to or otherwise complementary to ones which are restored. Conservation strategies include acquiring and protecting areas where existing marsh can expand. Adjusting development practices that will interfere with upland marsh expansion or future restoration opportunities is another important strategy. Conservation policy options include incentives to remove barriers to marsh migration and regulations that support development practices that protect sensitive resource areas where there is potential for adjacent restoration. This may include identifying areas for restoration adjacent to current healthy marshes and protecting those healthy marshes, especially where the adjacent uplands currently include complementary habitats that would contribute to a diverse landscape.

Sustaining new habitats that are created when current ones become unviable under future conditions will be an emerging management challenge. Choices will have to be made between enabling a transition versus aggressive restoration in the face of unsuitable conditions. Also important for restoration is creating conditions conducive to marshes being able to "restore themselves", e.g., through ditch modification to increase hydrologic connectivity or by working to reduce localized nonclimate stressors that can be controlled (see Section 2.4.2).

A more specific restoration project identified is removing tidal restrictions. Restoring tidal connections and removing or reengineering restrictions (e.g., culverts, road crossings, and tide gates) are already important management tools. Tidal restrictions—including levees, dikes, dams, and filling and channeling activities—change the natural flow of freshwater and sediment into the marsh. Restoring tidal connections enables sediment and tidal flows to distribute along natural gradients throughout the marsh, which may help the marsh to respond to changes in climate and keep pace with sea level rise. Since changing conditions may impact the amount and timing of freshwater flow, it will be important to use up-to-date precipitation and flow data and consider potential future climate scenarios when making assessments regarding reengineering designs. Once tidal restrictions have been removed, the most efficient way to achieve upstream restoration may be to facilitate favorable conditions for the marsh to "restore" itself. For instance, as the salinity regime adjusts to the restored flows, invasive *Phragmites* will die back, and the key will be to manage the transition so that native high marsh can return to fill that space. Controlling invasive species was another specific restoration project discussed. Since one characteristic of invasive species is the ability to thrive after disturbance, reducing the prevalence of invasive species aids adaptation by restricting competition while native species recover after future climate-related disturbances. *Phragmites* was the invasive species discussed at the workshop and is one of MBP's current invasive removal priorities, but MBP also currently controls for other marsh species such as Pepperweed and is monitoring emerging threats such as invasive tunicates, algae and crabs.

2.4.2. Reducing Nonclimate Stressors

Reducing nonclimate anthropogenic stressors of concern is another category of recommended adaptation strategies, one that especially needs to be considered in conjunction with conservation and restoration efforts. Healthy habitats will be better able to survive climate related stressors if they are not also struggling under the pressure of nonclimate stressors. This applies to both maintaining healthy priority conservation sites and ensuring that restoration projects are successful and able to become established.

Some of the management strategies discussed for reducing nonclimate stressors include nutrient management and methods to limit erosion. Excess nutrients favor invasive *Phragmites* over native marsh species. For reducing excess nutrient inputs, both point and nonpoint nutrient sources are of concern. Tools include upgraded wastewater treatment, upgraded combined sewer overflow systems and stormwater best management practices that slow the flow of stormwater (e.g., swales or buffers) and provide opportunities for nutrient filtration before it reaches the marsh. These practices also include land use policies that promote more absorbent land cover (e.g., through landscaping best management practices and policies that reduce impervious cover) and “rain catchers”. Erosion control options discussed include creating “no wake zones” in areas where wave energy from boat wakes is contributing to marsh edge erosion. Erosion control structures have the potential to be maladaptive (i.e., when structures designed to protect infrastructure redirect wave energy or interrupt sediment supply to the adjacent marsh). This risk that can be minimized through planning processes for protecting coastal infrastructure that are required to demonstrate that they will not magnify erosion effects on adjacent marshes. There is also the opportunity to highlight the buffering capacity of healthy marshes when planning efforts highlight potential trade-offs between protecting both infrastructure and marsh, in order to build support for marsh conservation and restoration efforts.

2.4.3. Planning and Monitoring

The last category of adaptation strategies discussed at the workshop addresses planning and monitoring, and the above categories each have planning and monitoring aspects to them. Many of the recommendations in Table 2-12 are based on planning, including prioritizing. Information needs were the basis of much of the discussion, including an exploration of a number of potential indicators of ecosystem responses to climate change. These indicators can help managers articulate some of the characteristics of the marsh that need to be examined first, in order to decide where to most effectively focus. Planning for restoration was discussed only so far as to recommend prioritizing restoring highest value habitats, leaving the question of how to determine which habitats have the highest value up to MBP. A related planning aspect related to conservation is how to determine where change is unavoidable, in order to manage the transition to a new habitat and the values that new habitat will provide. There is a need for management to have two plans: one to follow as long as maintaining current conditions is still possible, and another plan to follow once an unavoidable threshold is reached.

Monitoring priorities was another major aspect of the discussion. These included variables such as composition and structure of sediments, the position of the transition between high and low marsh and maximum growth rates. The ability to determine what the maximum level of vegetation growth is relative to sea level rise, and then to monitor changes in rates of growth and sea level rise, will be important for anticipating the threshold after which accretion will no longer keep pace vertically with sea level rise. Additional understanding of sediment fate and transport is needed. Storms and sea level rise will require attention in terms of how they impact sediment supply and erosion. Prioritization among management options for the two different types of erosion for Sediment Retention will depend on how storms and sea level differentially affect nearshore and coastal erosion versus marsh edge erosion.

The discussion of adaptation strategies described above was broad and free-ranging. The next section will combine the analysis of the exercise results with the ideas in Table 2-12 to discuss top pathways for management given climate change and to identify specific adaptation options in response.

3. MAKING THE LINK TO MANAGEMENT

As detailed above, the workshop resulted in a large volume of information on the sensitivities of the sediment retention and community interactions processes to stressor interactions under current conditions and future climate scenarios. The next step lies in organizing this information into a form that managers can use to identify influences of particular importance upon which to focus management interventions and adaptation planning.

3.1. USING INFORMATION ON INFLUENCE TYPE AND DEGREE, SENSITIVITY AND RELATIVE IMPACT TO IDENTIFY KEY MANAGEMENT PATHWAYS

In the workshop exercise and group discussions, the experts generated three categories of information about the relationships in the influence diagrams: (1) the type and degree of each influence; (2) the sensitivity of each influence (including thresholds); and (3) the high relative impact of certain influences on the endpoints. All three categories of information should be considered in concert when interpreting management implications. This can be done by performing a “crosswalk” of all three categories of information in order to identify pathways of particular interest that connect each endpoint (Sediment Deposition/Retention or Saltmarsh Sharp-Tailed Sparrow Nesting Habitat) to stressors or drivers that can be addressed through particular management activities. The crosswalks as well as example pathways are presented below.

3.1.1. Crosswalks: Influence Type and Degree, Sensitivity and Relative Impact

The crosswalks for Sediment Retention and Community Interactions are presented in Tables 3-1 and 3-2. For each influence, information on type and degree, sensitivity, and relative impact is listed side-by-side, first for current conditions, followed by Climate Scenarios A and B. This allows for easy comparison of all three categories of information, across all three scenarios. The influences have also been rank-ordered based on the amount of information available for each in terms of agreement on influence type, degree, sensitivity, relative impact and threshold potential.

Table 3-1. Sediment Retention group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information

				Current			**Climate A**			**Climate B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
L	Storms	on	Marsh Edge Erosion	Direct prop (4)	I (4)	Secondary	Direct prop (4)	I (4)	Secondary	Direct prop (5)	I (4)	Secondary	1
J	Marsh High Water Level	on	Coastal and Nearshore Erosion	Direct disprop strong (4)	I(4)/H(4)	Primary	Direct disprop strong (4)	H (4)	Primary	Direct disprop strong (5)	H (4)	Primary	1
O	Freshwater Flow	on	Nutrient Inputs	Direct prop (5)	I (5)	Secondary	Direct prop (4)	I (4)	Secondary	Direct prop (4)	I (4)	Secondary	1
W	Sediment Supply	on	Sediment Deposition/ Retention	Direct prop (6)	I (5)	Primary	Direct prop (7)	I (6)	Primary	DDirect prop (6)	I (6)	Primary	1
Y	Sediment Deposition/Retention	on	Inundation Regime	Inverse prop (5)	I (5)	Secondary	Inverse prop (4)	I (4)	Secondary	Inverse prop (4)	I (4)	Secondary	1
DD	Sediment Deposition/Retention	on	Net Accretion	Direct prop (6)	I (7)	Primary	Direct prop (6)	I (7)	Primary	Direct prop (7)	I (7)	Primary	1
FF	Below Ground Biomass	on	Net Accretion	Direct prop (7)	I (7)	Primary	Direct prop (5)	I (5)	Primary	Direct prop (5)	I (5)	Primary	1
B	Marsh High Water Level	on	Inundation Regime	Direct prop (6)	I (5)	Primary	Direct prop (5)	I (5)	↑	DDirect prop (6)	I (5)	↑	1

Table 3-1. Sediment Retention group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information (continued)

				CURRENT			CLIMATE A			CLIMATE B			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
C	Storms	on	Inundation Regime	Direct prop (5)	I (5)	Primary	Direct prop (6)	I (6)	Primary	Direct prop (5)	NA	Primary	2
R	Tidal Exchange	on	Inundation Regime	Direct prop (6)	I (6)	Primary	Direct prop (5)	I (5)	Primary	Direct (6)	I (4)	Primary	2
AA	Marsh Edge Erosion	on	Sediment Deposition /Retention	NA	I (5)	Secondary	Inverse prop (4)	I (5)	Secondary [threshold]	Inverse prop (4)	I (5)	Secondary [threshold]	2
E	Nutrient Inputs	on	Below Ground Biomass	Direct (4)	I (4)	Primary	Inverse (5)	I (4)	Primary [threshold]	Inverse (5)	I (4)	↑ [threshold]	3
I	Storms	on	Freshwater Flow	Direct prop (6)	I (5)	Secondary	Direct prop (5)	I (4)	Secondary	Direct (7)	NA	Secondary	3
K	Storms	on	Coastal and Nearshore Erosion	Direct prop (5)	I (5)	Primary	Direct prop (4)	I (4)	Primary	Direct (7)	NA	Primary	3
Q	Coastal and Nearshore Erosion	on	Sediment Supply	Direct prop (6)	I (4)	Primary	Direct prop (5)	I (4)	Primary	Direct (6)	NA	Primary	3
V	Surface Roughness	on	Sediment Deposition /Retention	Direct prop (5)	I (5)	Primary	Direct (6)	I (4)	Primary	Direct (5)	I (4)	↑	3

Table 3-1. Sediment Retention group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information (continued)

				CURRENT			**CLIMATE A**			**CLIMATE B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
EE	Net Accretion	on	Sediment Deposition /Retention	Inverse prop (5)	I (6)		Inverse prop (4)	I (7)		Direct prop (4)	I (7)	[threshold]	3
A	Land Cover: Percent Impervious Cover	on	Nutrient Inputs	Direct prop (5)	I (4)		Direct prop (5)	I (5)		Direct prop (5)	I (4)		4
F	Altered Flows: Tidal Restrictions	on	Tidal Exchange	Inverse (4)	I (5)	Primary	Inverse (4)	I (5)	Primary	Inverse (4)	I (5)	Primary	4
H	Land Cover: Percent Impervious Cover	on	Freshwater Flow	Direct prop (4)	I (5)	Secondary	Direct (7)	NA	Secondary	Direct (7)	NA	Secondary	5
P	Freshwater Flow	on	Sediment Supply	Direct prop (6)	I (5)	Secondary	Direct (7)	NA	Secondary	Direct (7)	NA	Secondary	5
CC	Below Ground Biomass	on	Sediment Deposition /Retention	Direct prop (4)	I (5)	Secondary	Direct (4)	NA	↑ Primary	Direct (5)	NA	↓ Secondary	5
M	Coastal and Nearshore Erosion	on	Tidal Exchange	Direct (6)	L (4)	Very little impact	Direct (4)	NA	Very little impact	Direct (5)	NA	Very little impact	6
Z	Inundation Regime	on	Sediment Deposition /Retention	NA	I (6)	Primary [threshold]	NA	I (7)	Primary [threshold]	NA	I (7)	Primary [threshold]	6

Table 3-1. Sediment Retention group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information (continued)

				CURRENT			**CLIMATE A**			**CLIMATE B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
D	Nutrient Inputs	on	Net Accretion	Inverse (5)	NA	Secondary	Inverse (4)	NA	Secondary	Inverse (4)	NA	Secondary	7
BB	Inundation Regime	on	Below Ground Biomass	NA	I (4)	[threshold]	NA	I (4)	[threshold]	NA	I (4)	[threshold]	8
G	Altered Flows: Tidal Restrictions	on	Freshwater Flow	No Influence (4)	No Influence (4)		No Influence (4)	No Influence (4)		No Influence (4)	No Influence (4)		9
S	Inundation Regime	on	Surface Roughness	NA	NA	Primary	NA	NA	Primary	NA	NA	Primary	9
T	Freshwater Flow	on	Inundation Regime	Direct (5)	NA		Direct (5)	NA		Direct (5)	NA		9
U	Freshwater Flow	on	Surface Roughness	NA	NA	Secondary	NA	NA	Secondary	NA	NA	Secondary	9
N	Tidal Exchange	on	Nutrient Inputs	Inverse (4)	NA		NA	NA		NA	NA		10
X	Inundation Regime	on	Sediment Supply	Direct (4)	NA	Uncertain impact	NA	NA	Uncertain impact	NA	NA	Uncertain impact	10

Table 3-2. Community Interactions group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information

				CURRENT			**CLIMATE A**			**CLIMATE B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
B	Sea Level	on	Inundation Regime	Direct prop (6)	I (6)	Primary	Direct prop (5)	I (4)		Direct prop (5)	I (4)		1
C	Freshwater Flow	on	Salinity	Inverse prop (5)	I (5)	Primary	Inverse prop (5)	I (5)		Inverse prop (5)	I (5)		1
E	Land Use/Land Cover: Residential Development	on	Freshwater Flow	Direct prop (6)	I (6)	Primary	Direct prop (6)	I (7)		Direct prop (6)	I (6)		1
M	Nitrogen	on	Above Ground Plant Biomass	Direct prop (6)	I (6)	Primary	Direct prop (5)	I (5)		Direct prop (5)	I (5)		1
O	Inundation Regime	on	Ratio Low Marsh to High Marsh	Direct prop (6)	I (6)	Interactive with R	Direct prop (7)	I (7)	↑	Direct prop (5)	I (5)	↑	1
R	Nitrogen	on	Ratio Low Marsh to High Marsh	Direct prop (4)	I (4)	Interactive with O	Direct prop (4)	I (4)		Direct prop (4)	I (4)		1

Table 3-2. Community Interactions group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information (continued)

				CURRENT			**CLIMATE A**			**CLIMATE B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
S	Nitrogen	on	Ratio of Native High Marsh to *Phragmites*	Inverse prop (5)	I (7)	Interactive with V	Inverse prop (6)	I (6)		Inverse prop (5)	I (5)		1
D	Freshwater Flow	on	Inundation Regime	Direct disprop weak (4)	L (4)		Direct disprop weak (4)	L (4)		Direct disprop weak (4)	L (4)		2
L	Inundation Regime	on	Sedimentation	Direct prop (6)	I (6)		Direct prop (6)	I (6)	↑	Direct prop (5)	NA	↑	2
P	Inundation Regime	on	Saltmarsh Sharp-Tailed Sparrow Nesting Habitat	Inverse (7)	NA	Primary	Inverse prop (4)	I (4)		Inverse prop (4)	I (4)		2
Q	Sedimentation	on	Marsh Elevation	Direct prop (7)	I (7)		Direct prop (6)	I (6)		Direct prop (6)	I (6)		2
U	Above Ground Plant Biomass	on	Sedimentation	Direct prop (6)	I (6)		Direct prop (6)	I (6)		Direct prop (5)	I (4)		2

Table 3-2. Community Interactions group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information (continued)

				CURRENT			**CLIMATE A**			**CLIMATE B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
V	Salinity	on	Ratio of Native High Marsh to *Phragmites*	Direct prop (6)	I (6)	Interactive with S	Direct prop (6)	I (5)	↑	Direct (6)	NA	↑	2
CC	Below Ground Plant Biomass	on	Marsh Elevation	Direct prop (5)	I (5)		Direct prop (4)	I (4)		Direct prop (4)	I (4)		2
EE	Ratio of Native High Marsh to *Phragmites*	on	Marsh Elevation	Inverse disprop weak (4)	L (4)		Inverse (5)	I (4)	[threshold]	Inverse (5)	I (4)	[threshold]	3
A	OMWM	on	Inundation Regime	Direct prop (5)	I (5)	Primary	Direct (4)	NA		Direct (4)	NA		4
DD	Tidal Restrictions	on	Inundation Regime	Inverse prop (4)	I (5)	Primary	NA	I (4)		NA	I (4)		4
K	Inundation Regime	on	Nitrogen	Direct prop (5)	I (5)		Direct prop (5)	I (6)		NA	NA		5
G	Land Use/Land Cover: Residential Development	on	Ratio of Native High Marsh to *Phragmites*	Inverse (4)	I (4)		Inverse (4)	NA		Inverse (4)	I (4)		6
N	Inundation Regime	on	Salinity	NA	I (4)	Primary	NA	I (4)		NA	I (4)		6

Table 3-2. Community Interactions group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information (continued)

				CURRENT			**CLIMATE A**			**CLIMATE B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
Y	Marsh Elevation	on	Ratio Low Marsh to High Marsh	Inverse prop (4)	I (4)		Inverse (4)	NA		Inverse (4)	NA		6
AA	Marsh Elevation	on	Saltmarsh Sharp-Tailed Sparrow Nesting Habitat	Direct (7)	NA	Primary	Direct (6)	NA		Direct (6)	NA		6
BB	Ratio Low Marsh to High Marsh	on	Saltmarsh Sharp-Tailed Sparrow Nesting Habitat	Inverse (5)	I (5)	Some	NA	I (5)		NA	I (5)		6
J	Inundation Regime	on	Above Ground Plant Biomass	NA	NA		NA	I (4)	↑ Interactive with H	Inverse (5)	NA	↑ Interactive with H [threshold]	7
T	Nitrogen	on	Below Ground Plant Biomass	Inverse (4)	I (4)		Inverse (4)	NA		Inverse (4)	NA		7
F	Land Use/Land Cover: Residential Development	on	Ratio Low Marsh to High Marsh	Direct (5)	NA		Direct (5)	NA		Direct (5)	NA		8

Table 3-2. Community Interactions group crosswalk for comparison of influence type and degree, sensitivity and relative impact for current conditions and climate scenarios. NA = no agreement; prop = proportional; disprop = disproportional; L = low sensitivity; I = intermediate sensitivity; H = high sensitivity; H-trend = no agreement but trending toward high sensitivity; ↑ = increasing relative impact from current; () = number of respondents; ranking column orders the influences according to completeness of information (continued)

				CURRENT			**CLIMATE A**			**CLIMATE B**			
Influence	**Variable X**	**on**	**Variable Y**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Influence**	**Sensitivity**	**Relative Impact**	**Ranking**
Z	Ratio Low Marsh to High Marsh	on	Above Ground Plant Biomass	Direct (6)	NA		Direct (6)	NA		Direct (4)	NA		8
FF	Ratio of Native High Marsh to *Phragmites*	on	Above Ground Plant Biomass	NA	I (4)		NA	I (5)		NA	I (5)		8
X	Ratio of Native High Marsh to *Phragmites*	on	Ratio Low Marsh to High Marsh	NA	NA	Some	NA	NA		NA	NA		9
H	Soil Temperature	on	Above Ground Plant Biomass	NA	NA		NA	NA	↑ Interactive with J	NA	NA	↑ Interactive with J	10
I	Soil Temperature	on	Below Ground Plant Biomass	Inverse (4)	NA		NA	NA		NA	NA		10
W	Salinity	on	Ratio Low Marsh to High Marsh	NA	NA		NA	NA		NA	NA		11

3.1.1.1. *Sediment Retention Crosswalk*

For Sediment Retention (see Table 3-1), there was agreement on type/degree and sensitivity across all three scenarios for over one third of the influences. Especially when coupled with a designation of high relative impact, these influences are of special interest for management because we have a good understanding of the nature of the relationships, their sensitivity to changes now and in the future, and their high relative impact on the endpoint of Sediment Deposition/Retention. Therefore these are influences for which management interventions are most likely to have the intended effects. Influences ranked number one in Table 3-1 fall into this category. Influences of ranking two are of almost equal status, as each has only one instance of lack of agreement in sensitivity or type/degree under only one scenario.

Influences of ranking three and four were almost all identified as having high relative impact and quite a bit of agreement on type/degree and sensitivity, as well. However, these influences each had more than one instance of lack of agreement, i.e., gaps across multiple information categories and/or across multiple climate scenarios.

The remaining rankings (5 through 10) continue the pattern of gradual loss of information. Some influences had high relative impact but lacked agreement on many (or even all) other categories of information. For these influences the implication is that, while each is believed to have significant potential to impact the end point, there is little concurrence on the actual mechanics of the relationship. However, it should be noted that Relationship BB (Inundation Regime on Below Ground Biomass) was tagged as a likely threshold relationship by the participants, where an inability to explain where the threshold might occur contributed to the lack of agreement (due to a mixture of codes) for this influence (see threshold discussion in Section 2.3.1.2 for further details).

In general, lack of agreement on one or more of the type/degree and sensitivity categories may be an indication that more information is needed to understand the particular influence. It does not imply that the relationship is not potentially important, but rather that there was not sufficient concurrence by this specific group of experts for managers to be confident about the response to either climate change or to associated management interventions. Relationship S (Inundation Regime on Surface Roughness) and Relationship U (Freshwater Flow on Surface Roughness) are interesting cases in that there was no agreement on influence type/degree or sensitivity, but there was agreement on high relative impact across all scenarios. In the case of these influences as well as others with multiple gaps in agreement, priorities for further investigation (through literature reviews and further basic research where needed) could be based in part on which of these influences are most critical to understand since they have a high relative impact or have links to other influences of special importance to the endpoint.

3.1.1.2. *Community Interactions Crosswalk*

For Community Interactions (see Table 3-2), there was agreement on both type/degree and sensitivity across all three scenarios for just over one third of the influences. Those coupled with a designation of high (or increasing) relative impact across the scenarios may be of special interest for management since they are well understood in terms of the nature of each relationship, its sensitivity to changes now and in the future, and its high relative impact on the Saltmarsh Sharp-Tailed Sparrow Nesting Habitat endpoint. These are the influences for which management interventions are most likely to have the intended effects. All of the influences of ranking one in Table 3-2 fall into this category. Within ranking two, there are two additional influences [Relationship L (Inundation Regime on Sedimentation) and Relationship V (Salinity on Ratio of Native High Marsh to *Phragmites*)] that are of nearly equal status in that they have high relative impact and nearly full agreement on type/degree and sensitivity across all scenarios, with the single exception of losing agreement on sensitivity under Scenario B.

Even though not designated as highest relative impact, the remaining influences of ranking two are equally important to consider. These are influences for which there was agreement on type/degree and sensitivity across all scenarios. While not of highest relative impact, these relationships are well understood and sensitive to change, and may be linked with other influences for important cumulative effects on the endpoint.

The rest of the influences ranked three to 11 follow a pattern of gradually increasing lack of agreement across multiple scenarios on type/degree and/or sensitivity. Again, lack of agreement on one or more of the type/degree and sensitivity categories indicates that more information is needed on the particular influence. It does not imply that the relationship is not potentially important, but rather that there was not sufficient concurrence by this specific group of experts, and more information is needed. In the case of Relationship H (Soil Temperature on Above Ground Plant Biomass) and Relationship J (Inundation Regime on Above Ground Plant Biomass), there was very low agreement for each on type/degree and sensitivity across the scenarios, yet there was agreement on high relative impact of the two relationships working together as an interactive influence under the climate scenarios. In the case of these influences as well as others with multiple gaps in agreement, priorities for research could be based in part on which of these influences are most critical to understand since they have a high relative impact or have links to other influences of special importance to the endpoint.

3.1.1.3. *Information Gaps*

3.1.1.3.1. Crosswalks

Patterns of information gaps in the crosswalk tables were similar for Sediment Retention (see Table 3-1) and Community Interactions (see Table 3-2). Over one third of the influences for both groups were well understood across type/degree and sensitivity categories of information across all scenarios. In quite a few additional cases, there was agreement on type although not on degree. Another common pattern for both groups is that influences of progressively lower rank tend to show lack of agreement under the climate scenarios first, while agreement under current conditions is often better. This drop in agreement across the scenarios is consistent with greater uncertainty about future conditions and ecological responses compared to current conditions. With such a variety of information gaps, it will be necessary to prioritize targeted literature reviews and/or basic scientific research to focus on key process components of interest. A starting point would be to establish a basic understanding of type and degree under current conditions for influences within otherwise well-understood pathways that link to rich opportunities for management. From there, the next step would be improving understanding of type/degree and sensitivity under potential future climate conditions, which will be less likely to be fully supported in the existing literature and may require theoretical approaches. Another method for sorting through and prioritizing "nonagreement" influences for further study might be to start from the perspective of management opportunities. Managers could look at their most tractable and effective management strategies currently available, and trace pathways from the associated management-related variables down to the endpoint of interest, as a means of identifying and selecting priority influences for research. Examples of promising pathways are presented in Section 3.1.2 below.

3.1.1.3.2. Confidence

Confidence estimates were not included in the crosswalk tables or used as a means of identifying management pathways because of extensive information gaps in the form of missing estimates. It is possible that this was partly due to time limitations as participants prioritized characterizing the influences before marking confidence. This may have been exacerbated by lack of familiarity with the coding scheme and the limited time that was available to discuss the definitions of high and low evidence and agreement.

Another problem that may have led to gaps was that the confidence exercise did not take into account specialty areas of participant knowledge. Due to the complex and interdisciplinary nature of the influence diagrams and the individual specialties of the participants, some participants may have been asked to make judgments on influences for which they felt they had insufficient expertise. In some cases they may have elected to leave those cells blank rather than indicate low confidence, as that would have incorrectly indicated that the participant knew that the scientific literature is lacking evidence or agreement on the influence, when really it was a case of lacking familiarity with the literature.

Thus the large number of missing cells for confidence could have been due to one or more of the following: (1) lack of time; and (2) confusion about the confidence definitions and coding scheme; and (3) inability to judge confidence in certain influences due to lack of expertise. These problems could be corrected in subsequent workshops through preworkshop trainings to increase familiarity with using the coding scheme; provision of a code to allow participants to indicate lack of expertise as a reason for leaving a cell blank; and additional time to complete the exercise.

3.1.2. Identifying Key Pathways for Management

Using the crosswalk tables (see Tables 3-1 and 3-2), it is possible to identify influences that are well understood, become more sensitive, and have a greater relative impact under future climate scenarios. By combining a series of such influences into a pathway to the endpoint, we can begin to identify key responses and changes in variables of interest to management. A “pathway” is defined as a series of connected variables and their influences, beginning with a driver or stressor variable and ending at the endpoint. The purpose is to be able to apply management interventions in order to impact the endpoint. “Management levers” are those variables for which it is possible to intervene with management options; the clearest connections to management options are for the top-level variables that are drivers or stressors. When multiple management levers are available for a pathway, the one that was more completely characterized or that had potential changes under the climate scenarios identified was selected. An example pathway from the Community Interactions process (see Figure 3-1) is described here, to show the process by which these types of pathways can be analyzed. This will be followed in the next section by summary diagrams showing the top three pathways of interest for each process, along with discussion of specific management options.

The Community Interactions example pathway (see Figure 3-1) begins with the management lever is Land Use/Land Cover: Residential Development, which affects Freshwater Flow (Relationship E). The pathway then goes to Inundation Regime (Relationship D) to Nitrogen (Relationship K), to the Ratio of Native High Marsh to *Phragmites* (Relationship S), to Marsh Elevation (Relationship EE), to the Saltmarsh Sharp-Tailed Sparrow Nesting Habitat endpoint (Relationship AA). During discussions, several participants noted that the diagram

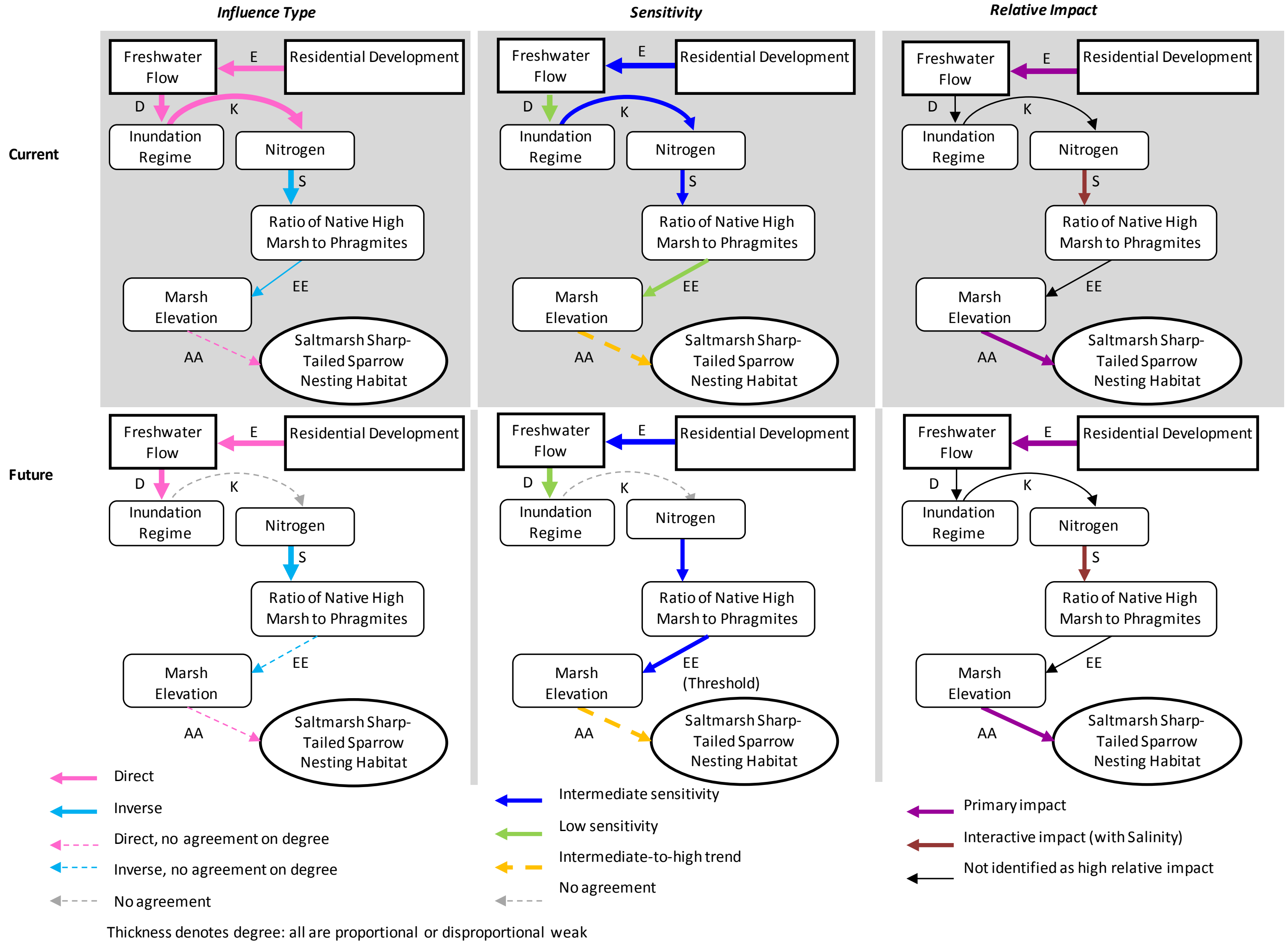


Figure 3-1. Community Interactions example pathway. Future = Climate Scenario B.

lacked an arrow to show the direct influence of Residential Development on Nitrogen; however the diagram did capture the indirect linkages of Residential Development with Nitrogen through Freshwater Flow via Inundation Regime. Nitrogen is delivered to the marsh through a number of pathways such as marine and freshwater sources along with stormwater runoff. Both direct disturbance from development and changes in nitrogen in the marsh will impact marsh vegetation, differentially affecting native high marsh and *Phragmites* growth.

Relationship E was characterized as a direct proportional influence of intermediate sensitivity under all scenarios. It was also identified as of primary relative impact. Relationship D was characterized as disproportionately weak direct influence under all scenarios. It was characterized as a low sensitivity influence under all scenarios and not identified as having high relative impact. Relationship K was characterized under current conditions as a direct proportional influence with intermediate sensitivity. Under the climate scenarios Relationship K was less understood, with no agreement on type or degree of influence or sensitivity under either climate scenario. Relationship K was not identified as having high relative impact under any of the scenarios.

Relationship S had more agreement, as it was characterized as an inverse proportional influence with intermediate sensitivity under all scenarios. Relationship S was identified as having a high interactive impact with Relationship V (Nitrogen on the Ratio of Native High Marsh to *Phragmites* with Salinity), and this relative impact remained the same under the climate scenarios.

Relationship EE was characterized as an inverse, disproportionately weak influence under current conditions, and an inverse influence with no agreement on degree under the climate scenarios. For sensitivity, Relationship EE was characterized as having low sensitivity under current conditions and intermediate sensitivity under the climate scenarios, a change that indicates a threshold; as sea level rises, marsh elevation will become increasingly sensitive to the ratio of native high marsh to *Phragmites*. This is because *Phragmites* is more effective at trapping sediment (due to its large rhizomes located right at the surface) and thus better equipped to build elevation in place. More importantly, if the shrinking of native high marsh accelerates due to the combined effects of *Phragmites* takeover and sea level rise, there could be an abrupt shift in the relative contribution of *Phragmites* to the ratio, leading to a change in the relationship between the ratio and marsh elevation. Relationship EE was not characterized as an influence with high relative impact under any of the scenarios.

Relationship AA was characterized as a direct influence under all scenarios, with no agreement on the degree of influence. The coding for sensitivity indicated a trend from intermediate-to-high sensitivity under all scenarios. Under current conditions, Relationship AA was identified as having primary relative impact, and this remained the same under the climate scenarios.

While there are aspects of this pathway that are not fully understood, it is a pathway that may be responsive to a variety of management options when planning for climate change. The management lever of Land Use/Land Cover: Residential Development is an ongoing concern for salt marsh habitats. Nutrient inputs, especially nitrogen, favor *Phragmites* over native species such as *Spartina patens*. These inputs can come from point sources such as sewage plants or nonpoint sources in the form of runoff that is exacerbated by residential development and associated increases in impervious surface cover. New or expanded residential development can also cause disturbance when adjacent to the marsh, which favors invasive species such as *Phragmites*. Thus this pathway emphasizes the priority importance of focusing on management options that prevent or mitigate disturbance of adjacent marshes during residential development, improve sewage treatment practices, and promote use of buffers, rain catchers and absorbent surfaces to reduce runoff.

3.2. TOP PATHWAYS AND IMPLICATIONS FOR ADAPTATION PLANNING

Section 3.1.2 above has used an example to demonstrate how the results of the expert elicitation exercise can be used to help identify key pathways for management. This method of identifying well-understood pathways that can be traced from endpoints of concern to management levers is a useful way to explore the implications of the workshop results for adaptation planning. In some cases it may be possible to identify management actions for immediate implementation, i.e., where there is sufficient understanding of the relationships among the variables as well as their sensitivities to act with relative confidence in the effects of management interventions. Additional pathways of interest can be identified through further examination of the crosswalk tables (see Table 3-1 and Table 3-2), using amount of information with agreement (to identify current best-understood influences) as well instances of climate thresholds (indicating potential climate-induced shifts) to identify “top pathways” of interest for management. This section describes three “top pathways” for the Sediment Retention and Community Interactions processes, as well as potential adaptation responses. This is followed by a brief review of MBP planning documents and discussion of where adaptation activities could be linked into these existing plans and strategies.

3.2.1. Top Pathways and Associated Adaptation Options

Three top pathways for each process are presented in Figure 3-2 (Sediment Retention) and Figure 3-3 (Community Interactions). For ease of viewing, each pathway is highlighted by a

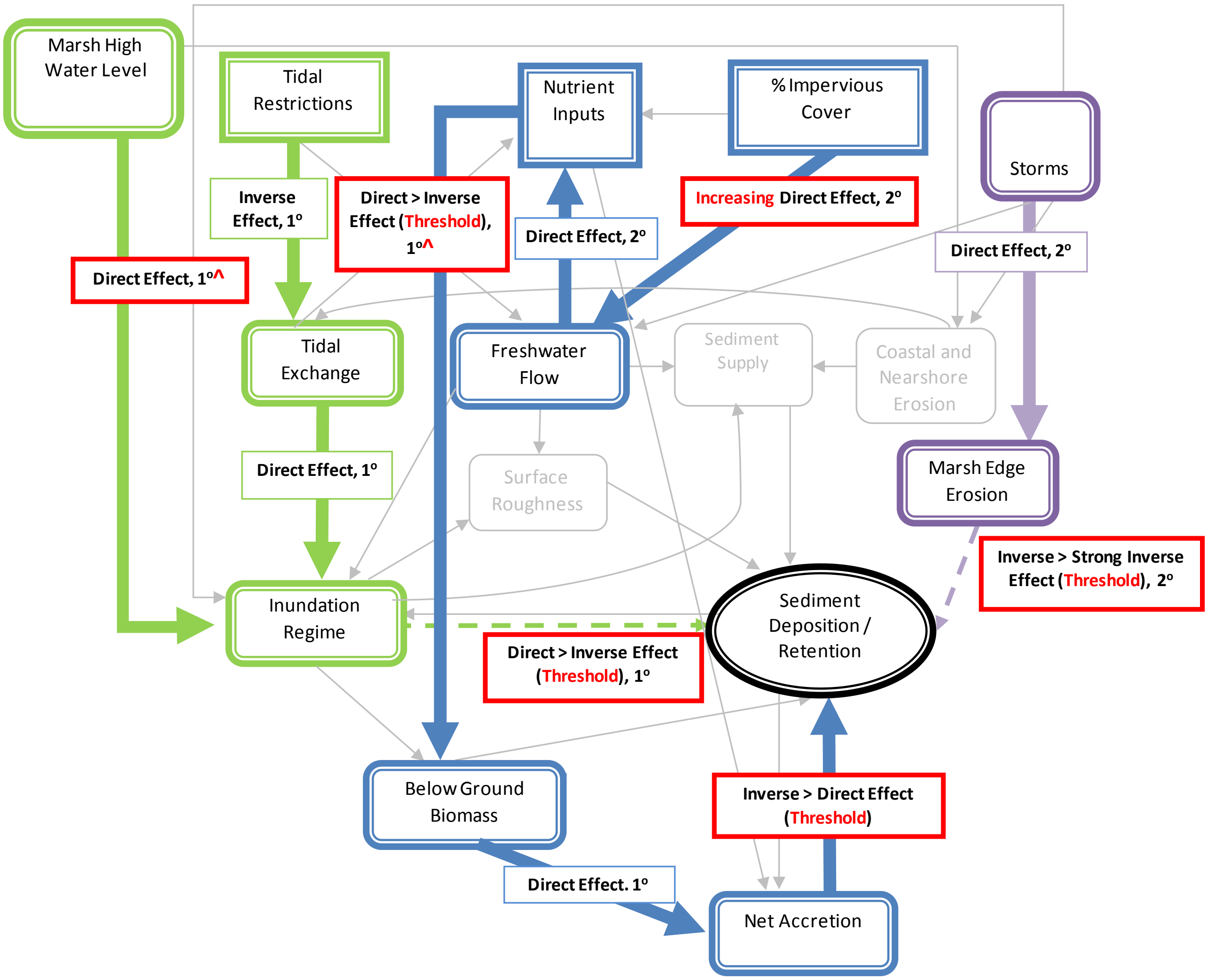


Figure 3-2. Top pathways for management of the Sediment Deposition/Retention endpoint. Green, blue and purple colors are used to distinguish different pathways. Red boxes highlight changes under future climate conditions. ^ indicates increasing relative impact under future conditions. 1° indicates primary relative impact under current conditions. 2°□indicates secondary relative impact under current conditions. A direct to inverse threshold occurs where there is a direct effect under current conditions that may shift to an inverse effect under future climate conditions. Dashed lines indicate inconsistent agreement across scenarios of current and future conditions.

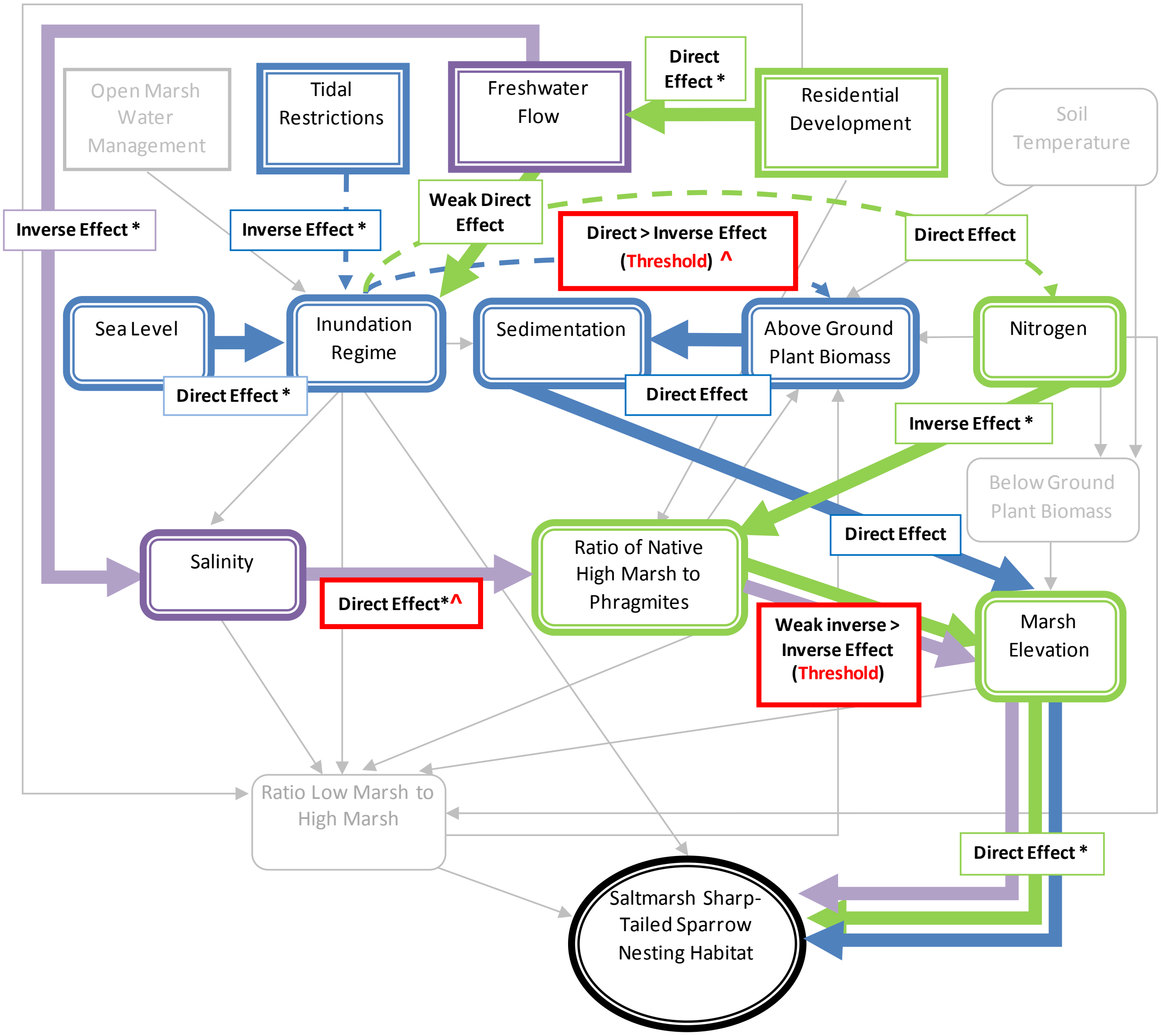


Figure 3-3. Top pathways for management of the Saltmarsh Sharp-tailed Sparrow Nesting Habitat endpoint. Purple, blue and green colors are used to distinguish different pathways. Red boxes highlight changes under future climate conditions. ^ indicates increasing relative impact under future conditions. An inverse to strong inverse threshold occurs where there is an inverse effect under current conditions that may shift to a very strong inverse effect under future climate conditions. Dashed lines indicate inconsistent agreement across scenarios of current and future conditions.

color (green, purple or blue), and influences that undergo changes under the climate scenarios are highlighted with red boxes indicating the nature of the change. Dashed lines indicate inconsistent agreement among participants in at least one scenario. The order in which the pathways are presented below is not an indication of order of importance. These are all management pathways with notable potential for addressing the climate sensitivities identified.

3.2.1.1. *Sediment Retention Top Pathways*

3.2.1.1.1. Purple pathway

In this pathway (see Figure 3-2), starting with the Sediment Deposition/Retention endpoint and working "up" the diagram, marsh edge erosion represents one major component of how sediment can be lost to the marsh. The relationship is an inverse effect where increased erosion leads to decreased sediment retention, and this was identified by the workshop experts as an effect of high relative impact (secondary category). Marsh edge erosion occurs when wave energy from wind-driven waves (especially during storms), boat wakes, and ice scour (removal of vegetation and underlying peat by tidal movement of overlying ice) lead to loss of sediment from the seaward edge of the marsh. The proportion of the eroded material that the marsh is able to retain through sediment trapping by marsh vegetation plays a major role in whether the marsh is able to rebuild along the eroded edge and to accrete vertically to keep pace with sea level rise within the interior. A threshold in sensitivity of the influence of erosion on sediment retention is explained below.

At the next level up the pathway, storms are a major contributor to marsh edge erosion; they have a direct effect which was characterized as having high relative impact (secondary category) on the endpoint. Marsh edge erosion is considered a threshold variable that is sensitive to future increases in storm intensity (with a strong seasonal component), especially given sea level rise. At a higher sea level, the marsh edge is exposed to storm surge and wave energy from storms for longer periods of the tidal cycle. Also, under Climate Scenario B, between 5 and 15% of East Coast storms (an additional one storm per year) are expected to move northward during late winter (Jan, Feb, March), further increasing storm energy effects in the Northeast. The greater influence of storms under the climate scenarios will intensify marsh edge erosion, and sediment eroded during storms will be more likely to be transported outside of the local marsh. The combined effects of sea level rise and changes in storms are likely to cause a threshold shift, where much of the sediment eroded from the marsh edge will no longer be available for accretion within the system, leading to an abrupt drop in sediment deposition and retention.

The management implications for adaptation under this pathway begin with a need to apply current erosion control tools, such as "no wake" zones to reduce erosion due to boat wakes. Barrier beaches that protect marshes from storms can be conserved through dune grass protection and restoration. Next, new tools for reducing wave action on the front edge of marshes need to be developed. These could include methods to establish oyster reefs adjacent to marshes exposed to storms or alternative protective barriers that reduce wave energy before it reaches the marsh edge. For these options to be successful, an improved understanding of the specifics of the local sediment budget, including coastal and nearshore sediment sources, will be needed for determining how, when and where to protect marshes against erosion due to storms. Monitoring of erosion and sediment transport at both the marsh edge and along the coastline will be increasingly important as the climate changes in order to detect threshold shifts, to identify areas losing sediment as priority sites for management intervention, and to measure effectiveness of such interventions. Another research area that would help prioritize most vulnerable areas for protection is monitoring the structure of the peat along the marsh edge. The age and structure of the marsh peat may put some areas at risk of passing the threshold earlier than others, necessitating their placement as highest priority for protection.

3.2.1.1.2. Green pathway

Starting with the Sediment Deposition/Retention endpoint and working along the Green top pathway (see Figure 3-2), Inundation Regime (frequency, depth and duration of marsh flooding) plays an important role in the delivery of sediment and the conditions necessary for its retention within the marsh. The relationship is considered a direct effect of high relative impact (primary category) under current conditions, where an increase in inundation leads to increased transport into, and deposition of sediment onto, the marsh. Under climate change, a threshold flip from a direct to an inverse relationship is expected when too much inundation increases tidal flow velocities and suspends more sediment than is deposited, leading to a net decrease in deposition and retention.

At the next level up the pathway, inundation regime is directly affected by marsh high water level, which is an indicator of sea level marked by the transition from marsh to upland vegetation. The ability of this transition zone to migrate upland with sea level rise will determine the extent (and even the existence) of the future marsh, and inundation regime will change accordingly. So with climate change, as sea levels rise and cause increasing pressure on the transition zone of marsh high water level, this in turn will have a greater impact on inundation regime and, ultimately, on sediment deposition/retention; therefore this is an influence of increasing relative impact under climate change. Marshes with barriers to migration will be limited to responding to sea level rise through vertical accretion only, as they will be unable to move upland (i.e., by adjusting the location of the marsh high water level/transition zone).

Meanwhile, another important determinant of inundation regime is tidal exchange, and this relationship was identified by the experts as having a high relative impact (primary category) on the endpoint. Tidal Exchange was defined by the participants as tidal prism, which is the difference between the volume of water at mean low tide and mean high tide. Tidal Exchange is in turn inversely affected by tidal restrictions, again with high relative impact (primary category). Tidal restrictions occur where infrastructure (e.g., roads, bridges, railroads, causeways and footpaths) cross wetlands such that insufficiently large openings (such as culverts and pipes) at tidal creeks alter the hydrology and salinity of the upstream marsh. The smaller the opening is relative to the volume of flow that needs to pass through in a tidal cycle, the less the tidal exchange. Tidal restrictions also affect the flow of freshwater downstream of the restriction.

Management options for this pathway are to remove or reengineer tidal restrictions and to remove barriers to upland migration of marsh high water level. In the near term, management options should continue efforts to relieve tidal restrictions in order to restore upstream hydrology, salinity and sediment transport across the restrictions. However, as sea level rise continues, it is possible that the inundation regime could reach a tipping point at which too much inundation could now have a negative effect on sediment deposition and retention. Tidal restrictions in the future could be managed to minimize excess inundation. Thus, this management lever will have to be used with care to avoid the unintended consequence of today‘s adaptation becoming tomorrow’s ‘maladaptation’.

One option to consider when reengineering tidal restrictions is the addition of tide gates so that the hydrology of the upstream marsh can be managed more precisely under the greater range of conditions expected in the future. Tide gates can be closed prior to storms or spring tides to avoid peak flooding, but reopened for normal tidal exchange. Other means to control hydrodynamic regime are through channel and ditch modification. Reduced flows have gradually led to wider and shallower channels; thus one way to restore hydrology is by cutting narrower, deeper channels within these altered channels. This would be especially effective in areas that have been diked or when done in conjunction with tidal restriction removals. Meanwhile, ditching has been used historically to increase drainage for mosquito control, and some ditch maintenance for that purpose continues today. There is an opportunity to work with the State Reclamation and Mosquito Control Board, which is responsible for ditch maintenance, to see where ditches have been maintained and compare their impacts on drainage and inundation regime to where they have been filled in or become revegetated. A long-term monitoring plan that includes sediment transport as well as inundation regime at different vegetation transition zones (including the marsh high water level) would allow for conditions to be consistently measured and may assist in understanding the level at which inundation causes a change in sediment deposition and retention in marshes.

Looking at marsh high water level together with tidal restrictions is important because tidal restrictions alter the marsh high water level upstream of the restriction. When prioritizing areas for removal or reengineering of tidal restrictions to restore upstream hydrology, there needs to be consideration of what the marsh high water level will adjust to once the vegetation adjusts to the restored hydrodynamic regime. Ideally, this can be done in such a way as to take advantage of the marsh's ability to 'restore' itself under the right conditions. Restoration prioritization should go to places where there is room for the restored marsh high water level to further migrate upland with sea level rise. Whether or not there is a tidal restriction, management options for marsh high water level are to remove barriers to migration such as roads and hardened shorelines. In areas without barriers, where the adjacent slope, soil and vegetation are suitable to marsh migration, there is a need for policies and incentives that discourage new barriers from being built and encourage conservation easements or other protections.

3.2.1.1.3. Blue pathway

Starting from the Sediment Deposition/Retention endpoint, the Blue pathway (see Figure 3-2) begins with a link to net accretion. Net accretion was defined by the group as referring to net change in elevation, which under current conditions has an inverse effect on sediment deposition and retention. Increased accretion decreases sediment deposition because the additional elevation reduces flow velocities during inundation to the point where more sediment will come out of suspension before it makes its way very far into the marsh. With higher sea level, a threshold shift could occur, changing this to a direct relationship. The mechanism behind this threshold is that when the marsh is at a greater depth during inundation, the water will arrive at higher flow velocities, carrying sediment still in suspension further into the marsh to be deposited.

The next influence in this pathway is the effect on net accretion of below ground biomass, which comprises the biological component of net accretion. It has a direct effect and is of high relative impact (primary category). Nutrient inputs, in turn, have a direct impact on below ground biomass under current conditions, also of high relative impact (primary category). This relationship works through nutrient additions being beneficial to above ground productivity, a portion of which adds to below ground peat. However, a threshold can occur where excess nutrients will have a negative impact on below ground productivity and increase decomposition. In the long term under the climate change scenarios, these effects are likely to outweigh the benefits of above ground productivity and cause the relationship to change from direct to inverse. This threshold change would increase the already high relative impact of this influence.

In the next step of the pathway, freshwater flow directly affects nutrient inputs, with high relative impact (secondary category) on the endpoint. Finally, at the management lever end of the pathway, freshwater flow is directly influenced by the amount of impervious cover, which delivers a greater portion of precipitation to rivers and streams, circumventing infiltration. The relationship is of high relative impact (secondary category). This relationship is likely to increase in sensitivity under the climate scenarios, as the effects of storms and flashiness of precipitation events increase.

Management options under this pathway should focus on both reducing nutrient sources and reducing delivery of nutrients through improved stormwater management. Stormwater management policies can promote the use of absorbent land cover (e.g., permeable pavements), rain catchers and buffers. In order to reduce direct nutrient sources, sewage treatment plants can be upgraded to tertiary treatment, which removes nutrients. Likewise, combined sewer overflow (CSO) systems can be upgraded to ensure that all sewage passes through upgraded treatment. CSO upgrades will become a high priority under climate change as larger precipitation events that trigger overflows are expected to become more frequent. Septic systems should be appropriately sited, regularly inspected and properly maintained. Education and outreach efforts can inform homeowners of proper timing (not directly before or after any rainfall event), placement and application rates for fertilizers.

3.2.1.2. *Community Interactions Top Pathways*

3.2.1.2.1. Green pathway

The Community Interactions example pathway described in Section 3.1.3 above is elaborated upon here as the Green top pathway (see Figure 3-3). Starting with the Saltmarsh Sharp-Tailed Sparrow Nesting Habitat endpoint and working “up” the diagram, nesting habitat is directly dependant on marsh elevation, as nests must be located high enough to avoid inundation at maximum tide during the incubation period. Therefore this is a direct relationship of high relative impact. Because this is one of only three variables that feed directly into the nesting habitat variable in the influence diagram, and because all of the top pathways converge on this one relationship, marsh elevation is arguably the most essential feature of this diagram.

At the next level up the pathway, we look at the effect on marsh elevation of the ratio of native high marsh to *Phragmites*. Under current conditions, this relationship is considered a weak inverse influence; a decrease in the ratio of native high marsh to *Phragmites* would lead to a modest increase in marsh elevation because *Phragmites* is more effective at trapping sediment (due to its large rhizomes located right at the marsh surface). The relationship strengthens under the climate scenarios, where there is a mixture of codes moving from weak to intermediate; the workshop participants identified this as a threshold shift to a stronger inverse relationship. They cited rising sea levels as the cause of the increasing sensitivity, as *Phragmites* would be better equipped to migrate landward to higher elevations while continuing to more effectively trap sediment in place; thus *Phragmites* is expected to better maintain marsh elevation compared to native high marsh, which may lose elevation more rapidly. This leads to a trade-off between maintenance of marsh elevation/extent in the face of sea level rise (favored by *Phragmites*) to preserve filtration and coastal protection functions, versus maintenance of native high marsh grasses (preferred sparrow nesting habitat) that will more rapidly be overcome by rising seas. This greater vulnerability of native high marsh underscores how critical it will be for management of sparrow nesting habitat to include provision of adjacent upland areas to allow migration of native high marsh in advance of rising sea levels (see management discussion below).

Next, ratio of native high marsh to *Phragmites* is inversely affected by nitrogen since nitrogen favors *Phragmites* growth over that of native high marsh. This is considered an effect of high relative impact on the endpoint. Nitrogen is in turn directly affected by inundation regime, which distributes and pools nitrogen-rich waters over the marsh. Inundation regime was defined slightly differently by the Community Interactions group compared to the Sediment Retention group, as the percent time the high marsh is under water during April−October. Inundation regime can be weakly affected (direct positive effect) by freshwater flow through its contribution to longer periods of inundation over the marsh. Finally, freshwater flow is directly affected by residential development, which has a high relative impact because increased impervious cover leads to greatly increased runoff.

Management options for adaptation based on the relationships in this pathway should simultaneously address both maintenance of marsh elevation and control of *Phragmites*. A good starting point would be intensifying efforts that mitigate the negative effects of residential development, which are already an ongoing concern for salt marsh habitats. The most direct options would be to promote more absorbent land cover (including permeable pavements) while also placing a priority on upgrades to treatment plants (to tertiary treatment) and improved stormwater management to reduce nutrient-rich runoff to marshes. At the same time, public programs can continue to raise awareness and create incentives for decreased use of fertilizers on lawns, regular inspections of septic systems, and use of rain catchers to reduce the volume of runoff during large rain events.

Meanwhile, management actions to preserve native high marsh while also maintaining marsh elevation will be essential. *Phragmites*, while better at maintaining marsh elevation, is undesirable as sparrow nesting habitat compared to native high marsh. *Phragmites* control programs (e.g., through mechanical harvesting or application of herbicides) should be targeted for implementation during or immediately after disturbance events from development projects (since disturbance favors invasions). However, it will be essential to couple this with removal of any barriers to marsh migration and protection of upland areas for native high marsh to grow and expand as sea level rises. Identification, acquisition and protection of such areas for marsh migration should focus on locations where room for marsh expansion is available and nitrogen sources are currently under best control for water quality maintenance.

3.2.1.2.2. Purple pathway

Starting with the saltmarsh sharp-tailed sparrow nesting habitat endpoint, the Purple pathway (see Figure 3-3) follows the Green pathway (see above) in its first two influences. As explained for the Green pathway, marsh elevation directly affects sparrow nesting habitat through a positive relationship of high relative impact. Marsh elevation is in turn inversely affected by the ratio of native high marsh to *Phragmites* (hereafter referred to as native high marsh: *Phragmites*); this inverse relationship is expected to intensify in the form of a threshold under climate change.

At this point the Purple pathway diverges from the Green pathway to focus on the effect of salinity on native high marsh: *Phragmites*. Greater salinity levels inhibit *Phragmites*, so any increase in salinity has a direct positive effect on native high marsh: *Phragmites*, and this influence is considered one of high relative impact on the end point. The designation of high relative impact for salinity—and also for nitrogen (Green pathway)—under current conditions is due to a competitive interaction between salinity and nitrogen that was identified by the workshop experts. Increased salinity has a negative impact on *Phragmites* while increased nitrogen has a positive effect. Salinity is expected to have an increasingly high relative impact under climate change as sea level rise leads to increased inundation of saline water for longer periods of time, and higher into the marsh (placing greater pressure on *Phragmites*). This is an instance in which a climate change effect actually supports the goal of maintaining native high marsh.

The last influence in this pathway is the effect on salinity of freshwater flows. This is an inverse effect because freshwater flow counteracts salinity through dilution. This is considered an influence of high relative impact under current conditions. Since both climate scenarios project an increase in precipitation in winter, spring, summer and fall (with the single exception of fall in Climate Scenario B), there is potential for this effect to increase in the future.

Management implications for adaptation under this pathway include some of the same actions as those discussed above for the Green pathway, as well as a few additional ones. Strategies for reducing freshwater runoff are further justified under this pathway since controlling runoff prevents salinity reductions that would favor *Phragmites* over the more salinity-tolerant native high marsh grasses. This places an even higher priority on the use of permeable pavements and rain catchers to mitigate freshwater runoff, since these options reduce nitrogen runoff while also helping to maintain salinity.

Other actions to maintain appropriate salinity levels can also be considered. These include controlling the hydrodynamic regime (including through channel creation/ditch modification) to maintain salinity through unimpeded inundation. Also advantageous would be restoration of riparian buffers and upstream freshwater marshes to reduce freshwater flows and favor local infiltration and storage of rain water.

3.2.1.2.3. Blue pathway

The Blue pathway (see Figure 3-3) shares the same first influence as the previous two pathways, but then it diverges to explore another set of variables that contribute to marsh elevation. We have already established that Saltmarsh Sharp-Tailed Sparrow Nesting Habitat is directly affected by marsh elevation. Working “up” the blue pathway from here, marsh elevation is directly affected by sedimentation (the average concentration of suspended sediment in the water column), which contributes positively to marsh vertical accretion. The effect on sedimentation of above ground plant biomass is also direct and positive, as plant material serves as a source of organic sediment that contributes to sedimentation.

In the next step of this pathway, inundation regime (percent time the high marsh is under water during April−October) has an important threshold effect on above ground plant biomass. Under current conditions the influence is direct: inundation regime favors above ground plant biomass since sufficient flushing through inundation prevents soil salinity from reaching levels that inhibit growth. Thus, just as an appropriate inundation regime is important for maintaining salinity (see Purple pathway above), it is also important for preventing salinity from becoming too high. Under the climate change scenarios, however, this influence shifts from a direct to an inverse effect. As sea level (which directly affects inundation regime) rises, inundation frequency and duration is expected to reach levels that cause increased hypoxia and result in marsh die-back (i.e., marsh drowning); therefore this influence is expected to have increasing relative impact on the endpoint.

Finally, inundation regime is inversely affected (with high relative impact) by tidal restrictions such as road crossings or other barriers to tidal exchange. This is considered an influence of high relative impact.

Adaptation options under this pathway center on supporting an appropriate inundation regime and protecting the ability of above ground biomass and sedimentation to maintain marsh elevation. Management of tidal restrictions will require care, as plans for both pre- and postthreshold conditions will be needed, as well as an ability to switch with agility from one management pan to the other. In the near term (under current conditions), ongoing efforts to restore tidal connections (e.g., remove tidal restrictions) continue to be advantageous. However in the longer term (at some point in the next 30−60 years under future climate change), these same efforts could become disadvantageous due to sea level rise, such that management should then switch to utilizing restrictions to manage the flows (e.g., through use of tide gates that allow control of flows).

Meanwhile, regardless of when a potential threshold change may occur in the relationship of inundation regime to above ground plant biomass, priority can continue to be placed on management activities that directly support the maintenance of above ground biomass and the ability of the marsh to accrete both vertically and landward with sea level rise. This includes actions to (1) identify, acquire and protect areas where marsh can grow and expand; (2) restore native high marsh habitat (with item #1 being a prerequisite); and (3) remove barriers to marsh migration. Furthermore all of these should be concomitant as much as possible with locations where natural flows and good sediment supplies are already in place.

To conclude this discussion of top pathways, it is worth noting that while this exercise has focused on management adaptations to climate change, there is also the potential for acclimation on the part of the Saltmarsh Sharp-Tailed Sparrow in the form of beneficial range shifts. Massachusetts is currently at the high end of the sparrows’ range. Under a warming climate, the MBP region could become the middle of the range, which would be beneficial to the overall sparrow population in the region. Breeding season and incubation period could actually decrease with warming, especially if the food supply improves. Currently, the timing of the nesting cycle is relatively fixed (consistently close to 26 days). If the sparrows could gain an advantage of needing one day less to nest, this could have a beneficial impact that could counteract some of the impact of sea level rise on tidal flooding of nests.

3.2.1.3. *Top Pathway Caveats*

Above we have described three pathways that scored as especially promising for successful management application in light of the information provided by the particular group of experts at this workshop. Given the complexity of these systems and instances of uneven agreement among participants, actions based on these pathways should be considered with care. A different set of pathways could be chosen based on additional meaningful criteria that are site specific and specific to individual managers' expertise. Based on their own knowledge of their sites, and/or input from different experts, managers are encouraged to examine the potential for additional top pathways for their own specific systems by examining the crosswalk tables and applying their unique knowledge.

While top pathways based on the expert knowledge from this workshop are useful, it is equally important to look at gaps in the crosswalk tables, where some influences did not show agreement in type, degree, and/or sensitivity. Lack of agreement does not necessarily mean there is no information available; often the experts did not agree based on competing evidence, or as a result of limitations of the expert elicitation process. In these cases, further investigation is needed. Where there are gaps in otherwise-strong pathways for management, further research—in the form of literature searches, data mining, or original research if needed—could be highly valuable.

A final consideration is that the influence diagrams do not explicitly represent temporal variability of stressors. In the Sediment Retention group, the issue of seasonality was raised. Components of seasonality can include storm frequency, timing and volume of precipitation, annual temperature range and number of days below freezing. These can affect multiple variables in the diagram such as storms, freshwater flow, nutrient inputs, sediment supplies, and biological factors such as below ground biomass. Just as managers need to consider the specifics of each site when making decisions about managing a particular pathway, they need to also account for timing considerations, including accounting for seasonality of certain stressors. For example, managers might focus on reducing boat wakes if marsh edge erosion is occurring in the summer, versus using protective barriers if marsh edge erosion is more of a problem during winter storms.

3.2.2. Adaptation Planning

There can be numerous approaches to climate change adaptation planning, including integrating adaptation into existing plans, or developing a stand-alone adaptation plan. This report focuses on the planning options for MBP, which as a National Estuary Program has several key management plans. The MBP management plans discussed here are used to demonstrate the type of adaptation planning that can be done to address the issues presented here. Other organizations can use their particular planning documents to apply the same approach.

MBP’s planning documents include a CCMP, which articulates long-range goals and objectives, a Strategic Plan for mid-term objectives, and an annual Work Plan that lays out short-term actions to implement the goals and objectives. Each of these plans addresses climate change and climate-related effects on some level, so it makes sense to use the results of this study to continue mainstreaming climate change into each of these planning scales. The 1996 CCMP considers sea level rise, including the context of acceleration due to global warming, but the accompanying actions are limited due to the associated uncertainty. The 2009–2012 Strategic Plan advocates for managers to “Adapt for projected impacts of climate change” as an emerging priority action area for implementing the CCMP. The FY11 Annual Work Plan (MBP, 2010) includes multiple proposed and ongoing projects with strong climate change connections. In this section we provide some links between MBP’s plans and the top pathways and management options discussed above; this set of examples is not comprehensive, but rather is meant to illustrate how the results of this study can be used to inform adaptation planning.

One management strategy outlined in the 1996 CCMP that pertains to the Purple Sediment Retention pathway (see Figure 3-2) is Action 13.1: “Municipalities should adopt and implement strict development/redevelopment standards within Federal Emergency Management Agency A and V flood hazard zones and other areas subject to coastal flooding, erosion, and relative sea level rise” (MBP, 1996). The relevance of the pathway to this action is that development activities can impact both coastal/nearshore and marsh edge erosion and these effects can be exacerbated through increases in water level and storms depicted in this pathway. Additional management options listed in Table 2-12 relevant to these development/redevelopment standards include “Identify, acquire and/or protect potential areas where marsh can grow and expand, and remove barriers to marsh migration” and “Work with programs responsible for coastal infrastructure to ensure that marsh protection is included in management plans”. This CCMP action is also relevant to the Green Community Interactions pathway (see Figure 3-3), as development standards affect how residential development impacts the ratio of native high marsh to *Phragmites* through disturbance or additional nutrient loading. Management options from Table 2-12 specific to these issues include “Improve stormwater management to reduce nonpoint source nutrient inputs into the marsh” and “upgrade sewage treatment plants (e.g., tertiary treatment) and combined sewer overflow systems to reduce the flow of excess nutrients into the marsh”.

Another strategy that relates to the Green Community Interactions pathway (see Figure 3-3) is CCMP Action 11.2: “The Regional Planning Agencies, in collaboration with the Department of Environmental Protection and municipalities, should expand upon current Massachusetts Bays Program efforts to identify nitrogen-sensitive embayments, determine critical loading rates, and recommend actions to manage nitrogen so as to prevent or reduce excessive nitrogen loading to coastal waters and groundwater" (MBP, 1996). This CCMP action is also relevant to the Blue Sediment Retention pathway (see Figure 3-2). While this action was likely designed in reaction to concerns about hypoxia in nitrogen-sensitive embayments, given that marshes are nitrogen sensitive, there is an opportunity to apply related actions to managing this pathway. There are multiple ways that residential development can increase nutrient loads. A starting point for determining where to focus nutrient-reduction management actions is better information on the relative contributions of point and nonpoint nutrient loadings. Especially when considering how the inundation regime may change nitrogen inputs to marshes under climate change, it is important to consistently monitor and manage nutrient loadings in the marsh. The 2009−2012 Strategic Plan (MBP, 2009) highlights this through the action "Promote and expand the role of volunteers and local officials in monitoring stormwater and receiving water quality and identifying sources of nonpoint source pollutants".

Wastewater carries high concentrations of nutrients that can be from either a nonpoint source such as areas around septic systems, or from a remote point such as sewage treatment plant outfalls. One applicable management option that several participants discussed would be to upgrade sewage treatment plants to tertiary treatment in order to reduce the flow of excess nutrients into the marsh. The 2009−2012 Strategic Plan articulates the means for implementing actions to manage nitrogen. One such action is to "Provide technical assistance to develop and implement wastewater management plans, including sewering efforts aimed at managing contaminant and nutrient loading to local embayments".

Additional nitrogen sources include lawn fertilizer and other landscaping sources. MBP is a key partner in the Greenscapes Massachusetts Program, which seeks to educate citizens and professionals about landscaping practices that have less adverse impacts on the environment. Residential development also affects stormwater management, which is another nonpoint nutrient source. The suggested management option in Table 2-12 of "Promote more absorbent land cover and "rain catchers" to prevent additional runoff", along with outreach, technical assistance and building guidelines, are potential options for reducing nutrient loads from these nonpoint sources.

Many of the current projects in the 2010−2011 Annual Work Plan are examples of management options that potentially could be informed by the results of this study. For instance, many of the projects include restoration activities. For the Green Community Interactions pathway (see Figure 3-3), one management option cited in Table 2-12 is "Control invasive species". The "Great Marsh *Phragmites* Monitoring and Control" project is directly relevant to this pathway, and work to date has included the development of a *Phragmites* control prioritization plan and a proposal for use of aerial photography to prioritize *Phragmites* control efforts throughout the Great Marsh. Factors within this pathway that could be identified from aerial photography to consider in the prioritization plan would be residential development and the ratio of native high marsh to *Phragmites*. Before investing in invasive species control in areas with residential development, it may be worth first implementing efforts to reduce disturbance or nutrient inputs.

The “Restore tidal connections” management option (see Table 2-12) is a major focus for both the Green Sediment Retention and Blue Community Interactions pathways, and for multiple projects in the Annual Work Plan. Implementation of the Cape Cod Natural Resources Conservation Service Watershed Action Plan will include restoration of 26 tidally restricted salt marshes and is an excellent example of how important this management option is to MBP. These projects could also consider another management option from Table 2-12, “Recognize and take advantage of the ability of marshes to “restore” themselves under the right conditions”, as removing tidal restrictions can create the “right conditions”.

Within each plan are a variety of additional opportunities for incorporating the workshop results. The examples offered here are intended to demonstrate the links, but are not comprehensive. In addition to the adaptation of current management projects and strategies, this study has identified sensitivities that may require the development of entirely new management options. Planning for future projects should identify opportunities to fill those needs and test new methods. In some cases it may even be necessary to reexamine and modify goals. Where impending threshold changes are unavoidable, it would be advantageous to have two plans: one to follow while species maintenance is still possible, and another plan (and goal) for after a threshold change has occurred. Thresholds aside, climate change will also raise new issues of conflicting goals due to trade-offs, and may result in additional situations where previous goals are no longer attainable. One example of potential conflicting goals in the future is between managing for sediment retention versus Saltmarsh Sharp-Tailed Sparrow habitat. As native high marsh is lost to sea level rise, will there come a point when it is advantageous to stop controlling *Phragmites,* given its sediment trapping and nutrient filtering capabilities? Even though *Phragmites* does not have the same habitat value as the native marsh, it could serve as a fringing buffer, should mudflat habitat replace the salt marsh. Thus in some cases, trade-offs may necessitate reevaluation of habitat goals, and even the application of a “triage” approach to prioritize certain habitats over others in the system.

4. CONCLUSIONS

This report has described the results of a vulnerability assessment aimed at synthesizing place-based information on the potential implications of climate change for key ecosystem processes, with the intent of enabling managers to undertake adaptation planning. The assessment involved identification of key management goals and ecosystem processes, conceptual modeling of those processes, a climate change sensitivity analysis in a workshop setting, and discussions/analysis of the potential applicability of the results for adaptation. The workshop exercise—an expert elicitation sensitivity analysis combined with management discussions—tested a novel approach for conducting "rapid vulnerability assessments" for ecological systems. The sections that follow discuss general observations, insights, and conclusions that emerged from the workshop exercise, from the analyses of management implications, and from our assessment of the methodology's utility for potential use in other locations/ecosystems.

4.1. INSIGHTS FROM THE WORKSHOP EXERCISE

4.1.1. Group Influence Diagrams

The group influence diagrams (see Figure 2-3 and Figure 2-8) were developed by the workshop participants based on edits to straw man diagrams prior to the workshop, followed by group discussions and refinement of a final group diagram during the workshop. While the main purpose of the group influence diagrams was to establish a framework for the subsequent sensitivity analysis, these diagrams represent key outputs in and of themselves. The construction of the diagrams proved to be an interesting group exercise in building a highly-constrained representation of a complex system, with only the most critical elements and interrelationships included. The iterative process of distillation into basic diagrams by the two interdisciplinary teams of experts resulted in some interesting differences in the Sediment Retention and Community Interactions diagrams.

The Sediment Retention group focused on the physical components of sediment processes as the highest priority factors influencing the balance of salt marsh accretion and erosion in their diagram, with less focus on biological factors. There appeared to be good familiarity with each piece of the diagram across all members of the group; this allowed them to be specific in defining (and hence envisioning the effects of) management-related variables (levers), which may have contributed to the high amount of agreement in judgments during the subsequent coding exercise. The participants reported that given the opportunity they would have added additional variables beyond the 15-variable constraint. Several participants noted that seasonality is an important variable that would have been added, especially as this variable would become even more of an issue under the climate scenarios. Components of seasonality can include annual temperature range and number of days in growing season (or conversely number of days below freezing). The participants decided to create a separate diagram showing the variables that would be affected by seasonality as a “confounding factor”. Participants were asked to consider seasonality and include notations in the “Notes” section as to any effect of these considerations on their judgments.

The Community Interactions group was also successful in agreeing on an acceptable influence diagram for the exercise. As with the Sediment Retention group, their diagram was complex, with a mixture of both physical sediment processes (which maintain marsh elevation) and biological processes (which determine shorebird nesting habitat and vegetation). The management levers within the Community Interactions diagram were primarily climate change stressors (e.g., sea level, soil temperature) versus ongoing human influence stressors (residential development). Several participants noted a lack of expertise in certain areas of the diagram, which led to a higher number of blanks in judgments than in the Sediment Retention group. Despite these factors, the level of agreement for the exercise was relatively consistent across the two groups.

A direct comparison of the Sediment Retention and Community Interactions diagrams is instructive in revealing important similarities and differences. There is significant overlap between the diagrams, which validates a common set of key “management lever” variables (i.e., tidal restrictions, impervious cover/residential development, freshwater flow, and nutrient inputs/nitrogen) that were selected independently by both groups. Some sedimentation-related variables are embedded in the community diagram (i.e., inundation regime, net accretion/marsh elevation); which is appropriate since maintenance of marsh elevation through sediment processes is essential to provision of sparrow nesting habitat. At the same time, the community diagram shows less detail on sediment supply processes in order to include variables on plant relationships that determine nesting habitat. The erosion component is the main element of the sediment diagram that is not explicitly represented in the community diagram. The community diagram includes both above ground and below ground biomass variables while the sediment diagram only includes below ground biomass. The one common relationship with somewhat conflicting results between the two groups is the influence of nutrients/nitrogen on below ground biomass. The Sediment Retention group identified this as an influence of increasing relative impact and a potential threshold, but the Community Interactions group did not. Hence this is a relationship for which further investigation is needed to explain the disparate findings.

In conclusion, while the two groups had different experiences and challenges in building their influence diagrams, both groups were effective in generating a useful representation of their ecosystem process for the sensitivity exercise. Participants reported that the highly constrained diagram-building procedure was productive in challenging them to focus on the most key elements of the system while still maintaining a sufficiently realistic model for sensitivity analysis. Designing the diagrams while considering current conditions, then applying climate scenarios to the same diagrams during the sensitivity exercise, worked smoothly. The one exception was the seasonality variable that several participants wanted to add to the Sediment Retention diagram; this variable was not added to the final diagram in order to allow enough time to make judgments for all of the existing influences. This and other complications could be avoided in future workshops by allowing the participants one more "iteration" with the diagrams after being briefed on the climate change scenarios. This would allow them to account for how future climate might raise additional variables for priority consideration in the diagrams.

4.1.2. Characterization of Influences

One technique for ensuring the effectiveness of expert elicitation is to break down the problem (i.e., what are the climate change sensitivities of the selected ecosystem processes?) into a set of distinct questions that clearly and explicitly define parameters and relationships of interest (see EPA's white paper at http://www.epa.gov/spc/expertelicitation/index.htm). This was accomplished by way of a systematized coding exercise—using the influence diagrams as a framework—in which the experts made a series of judgments about individual components of the system, in order to ultimately better understand the system as a whole. For each individual influence arrow in the diagram, each expert was asked to characterize the effect of variable "X" on the response variable "Y", including their confidence in that judgment. In future applications of this method, the complexity of the coding scheme could be greatly reduced by condensing the original 13 codes (see Table 2-2) down to the six typologies described in Section 2.2.2.5. This would reduce confusion and increase efficiency of the exercise. Nevertheless, using the pilot coding scheme, the experts were able to provide characterizations of all relationships in each process, and based on these results, some general observations of interest have emerged.

Participant notes and discussions revealed that for both processes, while there are many intermediate (and some high) sensitivity relationships among variables that are useful to be aware of for management, it was difficult to detect changes in sensitivities across the scenarios based on this method. Under the climate scenarios, one influence for the Sediment Retention group became highly sensitive while four others showed a trend (but no majority agreement) toward greater sensitivity; however, most of the sensitivities remained intermediate. For the Community Interactions group, there were two influences of low sensitivity, five influences with an intermediate-to-high sensitivity trend, and the majority being intermediate sensitivity under current conditions. Under the climate change scenarios there was one influence that decreased in sensitivity, while the majority of influences remained intermediate in sensitivity, or lost agreement. There were no influences which increased in sensitivity under the climate scenarios for the Community Interactions group. It was noted that the climate scenarios may cause thresholds to be reached in a number of different influences, though it was hard to determine at what point these thresholds would be reached. Two thresholds (Relationships E and EE, see Table 2-6) were indicated through coding in the Sediment Retention group, and one threshold (see Relationship G, Table 2-10) was indicated through coding in the Community Interactions group.

Yet outside of the coding exercise, there were indications based on participant notes and discussions that additional potential threshold relationships do exist. Identifying thresholds is challenging because while there may be general recognition of the potential for certain threshold effects, it can be very difficult to identify where—and especially when—a threshold may occur. Multiple potential thresholds were identified in both processes, through one of two ways. In some cases, participants tried to indicate thresholds with their sensitivity codes, but did so by including two codes under each of the scenarios to signal uncertainty as to when the threshold might occur. Others did not indicate the threshold with their codes at all because they were not sure whether the climate scenarios represented a big enough change to cause a threshold to be exceeded. In these cases, the thresholds indicated in Table 2-6 and Table 2-10 were ultimately identified through the participants' notes and discussions as relationships that could change dramatically at some point which is currently difficult to define.

Another way of identifying relationships of particular interest for management is to examine the relative impact of certain influences in the context of the whole process. For both processes, under current conditions the influences identified as having primary impact included variables spread throughout the diagrams, though there were several originating from the management levers and several closer to the endpoints (see Figure 2-6 and Figure 2-11). Under the climate scenarios, several of the management levers and influences going directly to the endpoint increased in relative impact for the Sediment Retention group (see Figure 2-7). The Community Interactions group only had a few influences increase in relative impact under the climate scenarios, none of which were directly linked to the endpoint (see Figure 2-11). This implies that while some variables related to management levers may become increasingly important as climate changes, there are a number of these variables that are less understood and may require additional monitoring and research.

Finally, characterization of interactions and confidence were also included in the sensitivity exercise, with mixed results. Trying to consider interactive effects of multiple variables moves the exercise to a much greater level of complexity. The number of possible pairwise interactions in the influence diagrams was very large, and the challenge of understanding combinations of effects could become very complicated. Thus the participants were not asked to attempt every possible pairwise combination, but rather were asked to indicate which interactions “jumped out at them” as well understood and important. Of course, even looking at all pairwise interactions would be a vast oversimplification because variables interact in greater multiples than just pairs. Nevertheless, while there were only a few pairwise interactions identified by enough participants to stand out, clearly these are relationships that are sufficiently well understood to merit consideration in management planning. With regard to confidence, the exercise made a good start of acknowledging the need to gauge confidence in the judgments and providing a systematic way for doing so; however, the large number of data gaps indicate that there were difficulties with this part of the methodology. Potential reasons for these difficulties, as well as potential improvements, have been discussed in Section 3.1.2.3.2. Both interactions and confidence are concepts that need further refinement and better estimation methods before they can be effectively interpreted for management planning.

4.2. APPLICATION OF WORKSHOP RESULTS

4.2.1. Top Pathways for Management

When using the workshop results, it is essential to examine all three types of information—influence type, sensitivity, and relative impact—when thinking about management applications. For some questions, one type of information may be useful individually, but because there are gaps and limitations within each type of information, a more complete management picture can be built using all three types together. It is helpful to focus on influences that are well understood, become more sensitive, and have a greater impact under future climate scenarios. In some cases, it is possible to connect a series of influences that meet these criteria to identify a path between the endpoint and a management lever. We have presented what we consider to be three top pathways for management (see Figures 3-2 and 3-3) for each process based on the information currently available from the workshop results. These delineate relatively well-understood relationships that are climate sensitive and for which there are consequent implications for management adaptation.

The climate-related changes of interest in the top pathways are of three main types: (1) changes in relative impact under climate change; (2) changes in sensitivity under climate change; and (3) threshold shifts under climate change. In the case of the influences for which relative impact is likely to increase under one or both future climate scenarios, and especially where relative impact is already high under current conditions as well, action could be taken immediately. These are influences for which there is sufficient understanding and opportunity to connect to management options that favor desirable outcomes, with increasing relative impact on the process as a whole as climate change continues. In the case of influences for which an increase in sensitivity is expected under climate change, there is still time to further study and anticipate the degree and timing of the sensitivity and to prepare best management responses. An expectation of increasing sensitivity could be considered a notification to managers to monitor and plan for when and how management practices should be adjusted to account for the impending change. Finally, in the case of thresholds, there is often a strong expectation that a threshold shift is likely, but usually a great deal of uncertainty as to exactly when the threshold will be crossed. Monitoring of threshold variables is needed so that managers will be alerted immediately to the shift when it occurs. In the meantime, actions can be taken to attempt to prevent the shift by keeping the system "below" the threshold as long as possible, while preparing a plan for what to do if an unavoidable shift occurs. After a shift occurs, managers should have a plan as to how they will manage the system differently in its new state, or whether they will take no action and instead shift their priorities to other goals.

It is important to note at this point that each pathway sits in the context of other influences with which there could be important interactions, so there may be opportunities for management options beyond those most directly evident from the main pathways. In the case of other management pathways for which there are currently information gaps based on the workshop results, it is vital to remember that lack of agreement does not mean zero understanding of influences or zero degree of sensitivity. Closer inspection can show that the agreement may be split between intermediate and high sensitivity, so the understanding that the sensitivity of the influence is important may be obscured by the distinctions between categories. It is of note that for influences for which there was agreement, the variation among participants was greater than that between scenarios. This could be due to a number of reasons: a limited range between the two mid-century climate scenarios; the number of assumptions each participant was required to make individually for each judgment; and the interdisciplinary and complex nature of the questions. This is an indication that these types of questions do not lend themselves to consulting a single expert, but rather require the combined judgments of a group of experts to complete the full picture. This also highlights the need for caution against relying solely on combined (agreement) information: the nature of the variation across participants is also important to consider.

Thresholds are clearly relevant to management, but usable information on thresholds remains elusive. Thresholds are considered likely, but can be difficult to identify in terms of how and when they will occur. A greater understanding of the location of potential thresholds—and the system's current proximity to reaching those thresholds—will be needed before managers can benefit from this type of information. Similarly, the data on interacting influences and confidence also raise some interesting issues, but should not be relied upon heavily for management decisions until their methodologies and comprehensiveness can be improved. Thresholds, interactions, and confidence are all important, but complex issues surrounding the understanding of ecosystem processes and vulnerability that are not regularly included in studies. Though they have not been fully integrated into this analysis, the results are an important step forward in our understanding of the system, and in the development of study methods.

4.2.2. Mainstreaming Adaptation into Planning

The vulnerability assessment results for the two ecosystem processes presented here are a big first step in the climate change adaptation planning process. We have given examples of ways to tie the vulnerability assessment results to potential management options as a starting point, but incorporating adaptation fully into management planning will require a more systematic and comprehensive process. Planning is an iterative process, especially for climate change adaptation, which is still a nascent field. Due to this iterative nature, the planning recommendations presented here are based on mainstreaming planning into existing planning mechanisms and documents, rather than developing a comprehensive, stand-alone adaptation plan. For MBP, nearer-term planning includes a multiyear Strategic Plan and an Annual Work Plan, both of which provide ways to insert specific management options into projects that are currently underway. In future plans, new projects that specifically incorporate climate adaptation priorities can be added. Repeating vulnerability assessments—once management options have been tested through project implementation—should be part of the iterative process. This is consistent with adaptive management approaches that emphasize “learning by doing”, by way of concrete steps to test a range of management choices, monitor and evaluate outcomes, incorporate learning into future decisions and regularly revisit and revise goals (Boesch, 2006). Finally, this study only covered two ecosystem processes and did not attempt to evaluate relative vulnerability or resilience across different ecosystem processes. The vulnerabilities of additional ecosystems, processes and goals will need to be assessed, taking into account what was most useful in the results of this study for adaptation. It may be useful to bring together a group of experienced resource managers to discuss the results of this expert elicitation and the resulting refined conceptual models and discuss how the results could be used to help MBP develop a set of specific climate change adaptation recommendations.

Thresholds remain a major unknown, and while much can be done to improve our understanding of factors affecting thresholds, some may only be revealed after they have been crossed. Thus it would be advisable for monitoring plans to be put into place to track indicators of state changes. Contingency plans for management actions once a system has changed states could be developed, as well as contingency planning for ways to respond to catastrophic events such as levee failures or earthquakes. Successful implementation of contingency responses will require that the political and scientific base be put into place now for responding properly following catastrophes or threshold changes.

In the meantime, when prioritizing implementation of adaptation actions, it is easiest to start with win-win options that contribute to current management goals and efforts while also responding to current and future climate change. Looking beyond the win-win options, many other actions will force managers to confront trade-offs that will require difficult policy decisions. One example highlighted in Section 3.2.2 is the trade-off between increasing coarse sediment supply from tributaries, which comes into conflict with current sediment reduction efforts for species habitats (such as oyster habitat). While a first step is to set up different best practices for species habitats, beyond that there may come a decision point when it is no longer possible to meet both goals, so a choice between the two conflicting goals will be necessary. As climate change progresses, there are likely to be more trade-offs, often between short and long term goals. Mainstreaming adaptation planning will provide a better chance of foreseeing conflicts between long- and short-term goals and identifying opportunities to build support for hard decisions and creative solutions.

4.3. GENERAL CONCLUSIONS

4.3.1. Transferability of Results and Method

The results of this study were developed for two specific ecosystem processes within a salt marsh ecosystem. Therefore the question arises as to how transferable the results may be. The sensitivities examined in this study are specific to sediment retention and community interactions in salt marshes, so the characterizations of influence type, sensitivity and relative impact cannot be transferred directly to other ecosystems and do not apply to different processes within these ecosystems. However, an example site was used as a way to focus the exercise and was chosen as a representative example of intact ecosystems; thus, the results could be transferable to other Massachusetts Bays locations in which the same ecosystem processes are present. The variables that ended up in the group influence diagrams are general enough that most of the results may transfer to the entire Massachusetts Bays system, with only a few specific enough to only apply to the Jeffrey’s Neck Marsh. In addition, it is likely that the influence diagrams could also be transferred for use with like ecosystems in other estuaries, with minor revisions for place-specific stressors or other process variables. The characterizations of influence type, sensitivity and relative impact would have to be revisited, particular to that location.

Where the specific results are not transferable, the methodological process is certainly transferable to other processes, ecosystems and locations. The methodology used for this assessment—an analysis of key ecosystem processes through expert elicitation—is a useful framework for understanding the current state of knowledge and research. The experts in this study were able to share their combined understanding of key processes and how they are expected to respond to climate change. The expert elicitation process also helped to identify where key gaps in understanding exist, what type of research is necessary, and how management should proceed. This methodology is transferrable in that the process used to compile, distill, and assess key information can be replicated. Expert elicitation is used in many fields of study and has been demonstrated here to be especially useful in understanding localized climate change impacts. Experts can think integratively across studies and disciplines and often have access to more current research and data than is currently available or published. As the climate change research is constantly evolving, this type of process is useful for synthesizing the most current information available. However, as climate change research is constantly changing, new information and research will need to be integrated concurrent with management decisions.

4.3.2. Utility of Method for Rapid Vulnerability Assessments

Given that the method is transferable, the question of utility arises: in what cases is this method advantageous? This method could be used again as a “rapid” vulnerability assessment, with opportunity for some of the improvements that have been suggested for some of the limitations. By “rapid”, we mean assessments that can be carried out within 6 months to a year, as opposed to assessments based on detailed quantitative modeling that can take multiple years. Another advantage is that this method is able to capture more recent knowledge than would be available from a literature review. It is also better able to capture more knowledge of the type that is closely related to management, which is less frequently published than scientific studies. Finally, the information is more integrated across disciplines and scales and is designed to better match the scale of adaptation decisions. In some cases new insights about management effectiveness may arise while in other cases existing understanding may be validated. Having a well-supported study to substantiate new and existing ideas can position managers to justify the most appropriate management options and priorities. It also can validate research priorities by highlighting known research gaps.

The disadvantages are that this method is designed to focus only on a specific piece of the system, compared to initial assessments that often rely on surveying the system more comprehensively (though less deeply), often through literature reviews. The amount of caution required to properly interpret the results is another disadvantage, given multiple limitations and caveats. The method is not intended as a consensus exercise, and the large number of influences without agreement present challenges to either fill those research gaps to improve agreement or to manage around limited information. In addition, this is only one group of experts, and another group could reach different conclusions. Group selection is critical to making sure appropriate areas of expertise and conflicting views on the system are represented. This is another reason why in addition to looking for areas of agreement, the results of individual judgments should also be examined. At the same time, since no participant can have complete expertise in every facet of a system, it is also important that participants have the opportunity to confer amongst themselves and adjust their judgments based on what they learn from each other.

Overall, the expert elicitation method developed for this study was well suited for achieving the purpose and goals of the assessment. In addition to achieving the workshop goals, several unexpected benefits emerged from the workshop. Participants reported that the combination of the development of the influence diagrams with systematic judgments facilitated thinking about the system and questions of climate change vulnerability in a different way than they had previously. Several expressed an intention to explore adapting the method for use in other workshop or classroom settings. Many participants found that the multidisciplinary interactions with colleagues were a valuable, personal learning experience, and that the group together generated new insights about the system and links to management that may not have been seen by individuals. In short, the method tested in this project offers opportunities to capture and integrate the existing collective knowledge of local experts, while pushing the boundaries to develop a new understanding of the system and management options in the face of insufficient data and deep uncertainty about future climate.

5. REFERENCES

Bertness, MD; Pennings, SC. (2002) Spatial variation in process and pattern in salt marsh plant communities in Eastern North America. In: Weinstein, MP; Kreeger, DA; eds. Concepts and controversies in tidal marsh ecology. New York: Kluwer Academic Publishers; pp. 39−57, DOI: 10.1007/0-306-47534-0_4.

Boesch, DF. (2006) Scientific requirements for ecosystem-based management in the restoration of Chesapeake Bay and Coastal Louisiana. Ecol Eng 26:6–26.

FitzGerald, DM; Fenster, MS; Argow, BA; et al. (2008) Coastal impacts due to sea-level rise. Ann Rev Earth Planet Sci 36:601−647. Available online at https://darchive.mblwhoilibrary.org/bitstream/handle/1912/2273/SEALEV~1.pdf?sequence=1.

Groffman, PM; Baron, JS; Blett, T; et al. (2006). Ecological thresholds: The key to successful environmental management or an important concept with no practical application? Ecosystems 9 (1):1-13, DOI: 10.1007/s10021-003-0142-z

Henrion, M; Breese, JS; Horvitz, EJ. (1991) Decision analysis and expert systems. AI Magazine 12(4): 64−91. Available online at http://www.aaai.org/ojs/index.php/aimagazine/article/view/919/837.

MBP (Massachusetts Bays Program). (1996) Comprehensive conservation and management plan: an envolving plan for action. U.S. Environmental Protection Agency, Massachusetts Executive Office of Environmental Affairs, Boston, MA. Available online at http://www.mass.gov/envir/massbays/ccmp.htm.

MBP (Massachusetts Bays Program). (2009) Massachusetts Bays Program Strategic Plan: April 2009-June 2012. April 1, 2009 Draft. Massachusetts Executive Office of Environmental Affairs, Boston, MA.

MBP (Massachusetts Bays Program). (2010) Massachusetts Bays Program FY11 Annual Work Plan: July 1, 2010 to June 30, 2011. Massachusetts Executive Office of Environmental Affairs, Boston, MA

Morris, JT; Sundareshwar, PV; Nietch, CT; et al. (2002) Responses of coastal wetlands to rising sea level. *Ecology* 83(10):2869–2877. Available online at http://www.ias.sdsmt.edu/staff/Sundareshwar/Reprints/morris%20et%20al%202002.pdf.

Morgan, MG; Henrion, M. (1990) Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis. New York: Cambridge University Press.

NECIA (Northeast Climate Impacts Assessment). (2006) Climate change in the U.S. Northeast: a report of the northeast climate impacts assessments. Union of Concerned Scientists, Cambridge, MA. Available online at http://www.climatechoices.org/assets/documents/climatechoices/NECIA_climate_report_final.pdf.

Pradhan, M; Henrion, M; Provan, G; et al. (1996) The sensitivity of belief networks to imprecise probabilities: an experimental investigation. Artificial Intell 85(1-2):363–397.

Scavia, D; Field, JC; Boesch, DF; et al. (2002) Climate change impacts on U.S. coastal and marine ecosystems. Estuaries 25(2):14–164.

APPENDIX A. DEVELOPMENTAL PROCESS FOR CLIMATE READY ESTUARIES VULNERABILITY ASSESSMENT

A.1. SELECT KEY GOALS, ECOSYSTEMS, AND ECOSYSTEM PROCESSES

The MBP partners participated in several discussions and meetings to outline management priorities, key resources to consult, and other considerations for selecting key goals for the assessment. As a starting point, MBP's Comprehensive Conservation and Management Plan (CCMP) (MBP, 1996; MBP, 2003) was examined and discussed to select four to six key management goals as a focus of the assessment. These goals would help to further refine the analysis to specific ecosystems, ecosystem processes, stressors of concern, and indicators for measuring changes in the ecosystem. Selected management goals included:

- Protect and manage existing wetlands
- Restore and enhance the habitat diversity and living resources of wetlands
- Protect submerged aquatic vegetation
- Prevent the spread of marine invasive species in order to maintain biodiversity

Following an October 2008 kickoff meeting with MBP staff and other local experts to gather scientific and management background information on the system, salt marshes were selected as the wetland habitat of focus for the project. These systems were identified as highly relevant to MBP's management goals due to their diversity, their habitat values for threatened and endangered species, their vulnerability to invasive species, and their sensitivity to climate-related variables such as sea level rise and altered hydrology. As a starting point for exploring linkages among such climate-related variables, their interactions with nonclimate stressors of concern, and the key ecosystem processes that maintain the system, a general conceptual model was developed.

A.2. CONCEPTUAL MODELS

The conceptual models were intended to serve as a framework for further analysis in the vulnerability assessment. The models depicted likely pathways by which climate drivers may directly or indirectly affect interacting stressors that impact ecosystem processes. The process is intended as iterative, as we learn from exploring the first two ecosystem processes, next steps can involve focusing on additional ecosystem processes, or for repeating a similar analysis for additional habitats. The development of the conceptual model has also served to help with narrowing process; we began with a comprehensive list of ecosystem processes and indicators and then chose those more important to and best representing healthy salt marsh functioning. The total number of possible ecosystem processes was narrowed down to five to six key ones for the ecosystem. The models also included a similar number of variables that may serve as indicators for the status of these endpoints. Ecosystem processes and indicators were identified in discussions among MBP and EPA ORD, as well as through examination of the Delta Regional Ecosystem Restoration Implementation Plan's conceptual models developed by the CALFED Bay-Delta Program (Schoellhamer et al., 2007; Kneib et al., 2008; San Francisco Estuary Indicators Team, 2008). To ensure consistency with current research, these ecosystem processes and indicators were cross-walked with locally-specific literature on climate change impacts (Ashton et al., 2007; Cavatorta et al., 2003; Frumhoff et al., 2007; Orson et al., 1998), as well as research on metrics and indicators for the region (Massachusetts Department of Coastal Zone Management, 2003; USGS-FWS, 2008).

Stressor interactions are stressors that may work independently or together to affect ecosystem functioning. These included both nonclimate and climate-related influences that stress salt marsh ecosystems. Preexisting stressors and stressor interactions were identified during the development of salt marsh conceptual model, and impacts of these stressors of concern were identified using the MBP Comprehensive Conservation and Management Plan.

Climate drivers are climate variables that may impact ecosystem processes directly (e.g., raise water temperature) or indirectly (e.g., cause changes in nutrient inputs). The climate drivers relevant to salt marshes were identified by first examining climate drivers for estuarine systems outlined in Synthesis and Assessment Product 4.4: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources* (CCSP, 2008), followed by extensive discussions among the MBP partners. The climate drivers were then mapped to the key processes of the ecosystem, either directly or through interactions with preexisting stressors. These pathways provided the basis for the development of the conceptual models. The pathways included are intended as a heuristic, without distinguishing between the magnitudes between them. It is not possible to include all possible system components, nor connections between them. The general salt marsh model is first presented, and then additional detail for individual ecosystem processes is described in the two submodels.

A.2.1. General Models

A.2.1.1. *Salt Marshes*

The general model for salt marshes in presented in Figure A-1. Climate drivers in the salt marsh conceptual model include: changes in air temperature, changes in precipitation, sea level rise, and changes in storm climatology and wind. Changes in air temperature refers to the variation from the climatological mean surface air temperature in a particular region. Changes in precipitation refers to variation from the climatological mean of the amount, intensity, frequency and type of rainfall, snowfall and other forms of frozen or liquid water falling from clouds in a particular region, changes refer to both the form and flow of precipitation. Sea level rise is defined as "relative sea-level rise," the change in sea level relative to the elevation of the adjacent land, which can also subside or rise due to natural and human induced factors. Relative sea-level changes include both global sea-level rise and changes in the vertical elevation of the land surface. Changes in storm climatology and wind refers to the variation from the climatological mean of the frequency, intensity and duration of extreme events (such as hurricanes, heavy precipitation events, drought, heat waves, etc.) and the changes in the direction and timing of the dominant seasonal winds.

Stressor interactions within the salt marsh conceptual model include: changes in water temperature, salinity, flooding, sedimentation and erosion, invasive species, pollutants, other human uses, altered flows, and land use/land use change. Changes in water temperature refers to variation in the climatological mean surface water temperature in a particular region. Changes in salinity are measured by variations in salinity concentration, with respect to lateral gradient or vertical stratification. Flooding is defined as an excess of water that does not recharge ground water beyond time frames typical for watersheds due to high precipitation events, storm surge, or infrastructure damage. Sedimentation and erosion includes the transport, deposition, and removal of soil and rock by weathering, mass wasting, and the action of streams, waves, winds and underground water. Invasive species are plants, animals or microbes not native to an area that are able to exploit a niche and disrupt native species, with negative impacts. Pollutants include any substance introduced into the environment that, because of its chemical composition or quantity, prevents the functioning of natural processes and produces undesirable environmental and health effects. Other human uses is a catch-all category based on the CCMP which includes the use of the marsh and surrounding area for activities such as fishing, shipping and ports, dredging, transportation projects, sand mining, recreational use, marinas, and industrial uses that may impact the marsh. Altered Flows refers to tidal restrictions or upstream

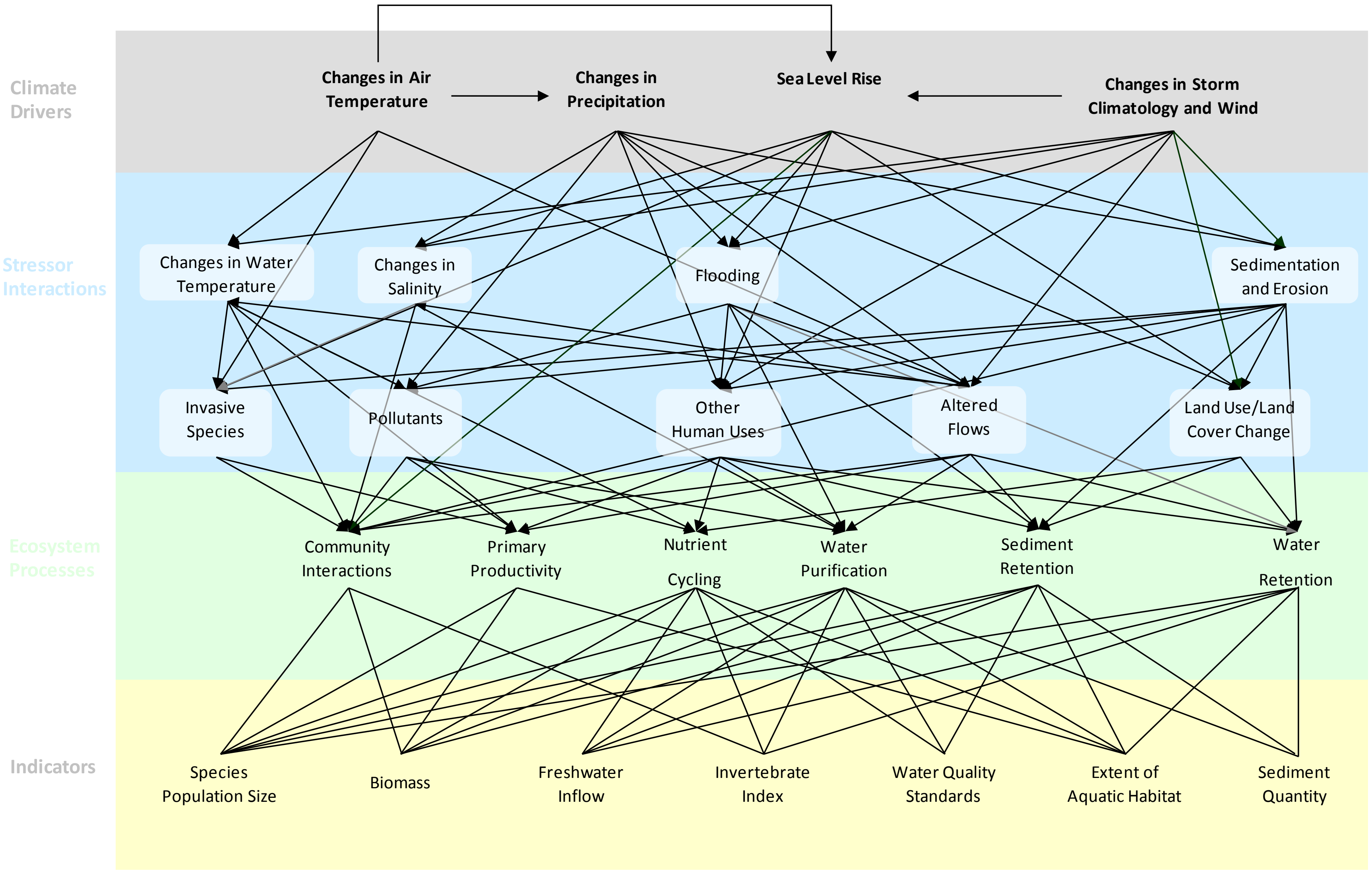


Figure A-1. Salt Marsh Conceptual Model.

water diversions for agricultural, industrial, transportation, or urban uses that change the natural flow of freshwater and sediment into the marsh, including leveeing, diking, damming, filling, or channeling. Land use/land use change is defined as the current use of marsh and human-induced changes to the marsh or surrounding land, including wetland alteration and expansion of the built environment.

Ecosystem processes in the salt marsh conceptual model include: community interactions, primary productivity, sediment retention, water retention, nutrient cycling, and water purification. Community interactions is defined as the interrelations among species within the ecosystem. Primary productivity is the production of energy by plants and phytoplankton within the entire system. Sediment retention is the balance between the processes of removal and deposition of suspended sediment. Water retention is defined as the capability to buffer against flooding. Nutrient cycling is the process of transfer of nutrients between organisms and the water. Water purification is defined as the removal of pollutants and harmful microorganisms.

Indicators within the salt marsh conceptual model include: species population size, water quality standards, freshwater inflow, sediment quantity, extent of aquatic habitat, biomass, and invertebrate index. Species population size is defined as the number of similar organisms residing in a defined place at a certain time, including threatened and endangered species, native species, and invasive species. Water quality standards are provisions of State or Federal law which consist of designated uses for waters of the United States, and water quality criteria for such waters based upon such uses. Criteria address the values for water quality indicators (e.g., water temperature, salinity, water contaminant exposure, biological thresholds for water contamination, nutrient concentrations, water toxicity) that are required to support designated uses. Freshwater inflow is the amount of freshwater inflow to the estuary from the watershed. Sediment quantity is defined as suspended sediment concentration. Extent of aquatic habitat is defined as the area of all contiguous, vegetated salt and brackish wetland, or mean width of marsh (may be divided into low or high marsh or by dominant species). Biomass is the presence and abundance of different species. The invertebrate index is the collection of metrics that are aggregated into a single score to measure the composition of the invertebrate community.

The salt marsh conceptual model focuses on a limited number of ecosystem processes that are key to the habitat and region. In some instances, a component of the system may fill roles at multiple levels, and the model does not represent all possible roles a particular component may fill. The model does not take the cumulative effects of climate stressors or tipping points/critical thresholds into account. The model does not include ocean acidification as a climate driver, as current understanding of salt marshes indicate it as secondary compared to the other stressors.

A.2.2. Submodels

Following the development of the general salt marsh ecosystem model, two ecosystem processes within the model were chosen for more detailed investigation. The purpose was to select good processes to start with to test out the method, but the choice does not imply that these are necessarily the most important, or the most vulnerable, processes. Sediment retention was identified as a key salt marsh process because of the importance of sediment supply to allow for marsh development and growth. In the Massachusetts Bays, sediment supply is influenced by a number of factors, including storms, heavy precipitation events, and human influences such as tidal restrictions and development. MBP and other regional partners have done extensive work on examining changes in sediment and how these changes may be influenced by changes in climate. This provided the basis for the development of the sediment retention submodel.

Community Interactions was chosen as the second ecosystem process of focus. To select a specific well-constrained "storyline" of interactions between two to four species for this process, ICF and EPA consulted with MBP and regional experts on key sensitivities for this process within the Massachusetts Bays system. The storyline focuses on the relationship of four species (*Spartina alterniflora*, *Spartina patens*, *Phragmites australis*, *Ammodramus caudacutus*). The Saltmarsh Sharp-Tailed Sparrow (*Ammodramus caudacutus*) prefers the native species of *Spartina patens* as habitat over the invasive *Phragmites*. The lower marsh *Spartina alterniflora* is likely to migrate upland with pressure from sea level rise, perhaps infringing on the upper marsh *Spartina patens*. Changes in freshwater flow will affect the less salt tolerant *Phragmites* with a major question of whether it will expand into the upper marsh range of *Spartina patens*. This storyline provided the basis for the development of the community interactions submodel.

A.2.2.1. *Sediment Retention*

The sediment retention submodel is presented in Figure A-2. It focuses on the balance between the processes of deposition and retention of sediment within a salt marsh and the resultant ability of the marsh to persist in the face of climate change. The accumulation of sediments and marsh vertical accretion result from interactions among tidal imports, vegetation dynamics, and depositional processes (Reed, 1995). Freshwater runoff and coastal storms transport and deposit sediments onto the marsh surface, and the roots and stems of marsh vegetation retain sediment that would otherwise be carried away from the marsh by wind and waves (Roman et al., 1997). Over time, the accumulation of dead and dying organic matter produces peat, and the combination of peat accumulation and sediment deposition gradually builds up the marsh surface. Ultimately it is the balance between marsh vertical accretion and

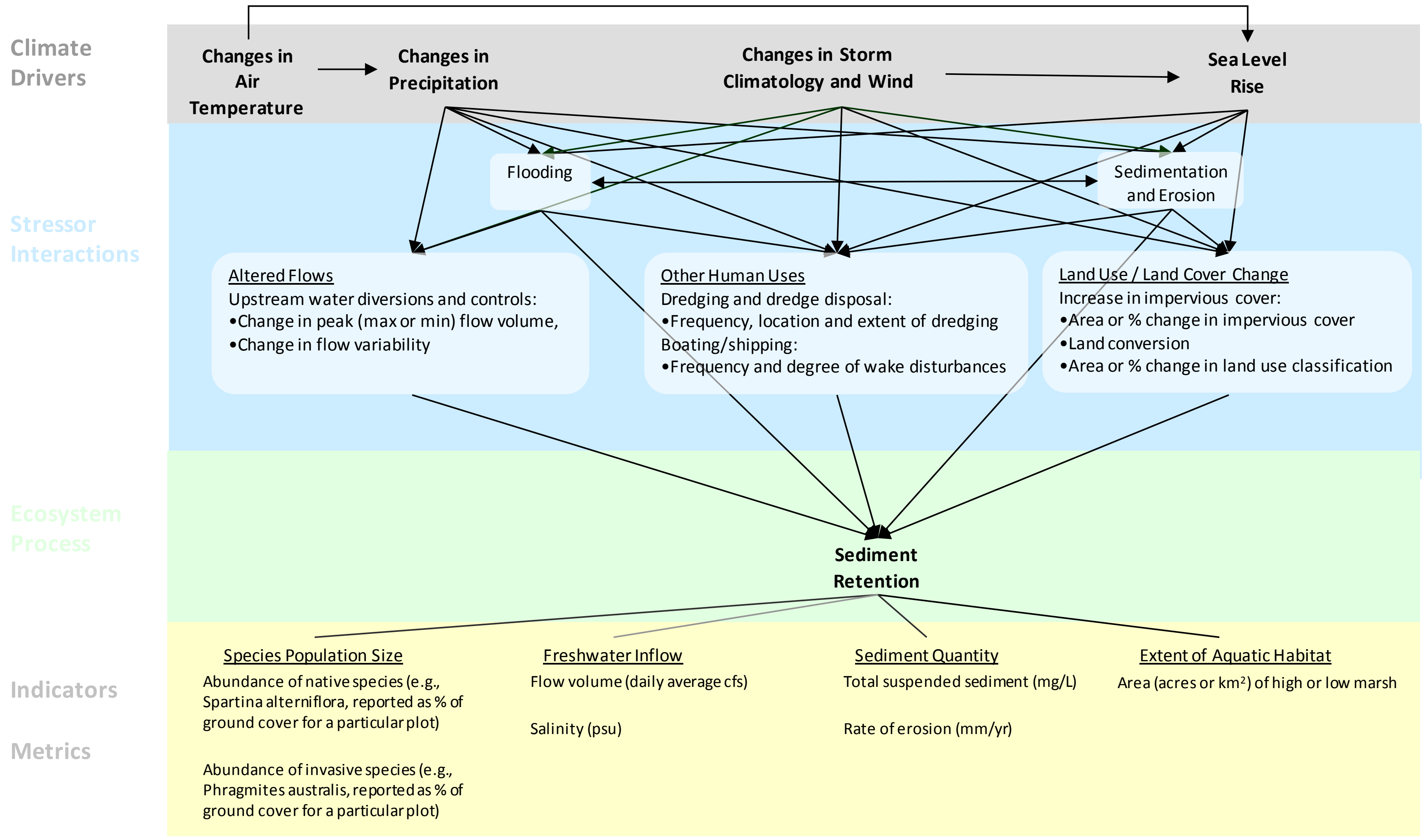


Figure A-2. Sediment Retention submodel.

sea level rise that determines whether a tidal marsh at any given location will persist in the face of rising seas by migrating inland or will convert to tidal flats or open water (Reed, 1995).

A number of key climate variables (air temperature, precipitation, storm climatology and wind, and sea level rise) and stressors (altered flows, other human uses, land use/land cover changes) may impact this process directly or indirectly. In New England marshes, altered hydrology typically includes tidal restrictions, which reduce the regular tidal flooding of marshes needed for marsh maintenance (Carlisle et al., 2002). At the upland edge, excess runoff from heavier precipitation events in areas with impervious surfaces may oversaturate marsh soils and reduce soil salinity. Increases in the frequency and intensity of storms can change the pattern of sediment transport along the shoreline, carrying more sediment away from the marsh and increasing erosion at some locations, reducing the sediment available for marsh development (Nyman et al., 1995).

A.2.2.2. *Community Interactions*

The community interactions submodel is presented in Figure A-3. This submodel focuses on the relationship of marsh vegetation zonation and the availability of nesting habitat for the Saltmarsh Sharp-Tailed Sparrow, *Ammodramus caudacutus*, a high-priority species for bird conservation in New England. The Saltmarsh Sharp-Tailed Sparrow nests in the high marsh zone to avoid nest flooding (DiQuinzio et al., 2002; Gjerdrum et al., 2005). Under undisturbed conditions, the low marsh is dominated by the tall form of *Spartina alterniflora*, and the high marsh zone is characterized by salt marsh hay (*Spartina patens*), black rush (*Juncus gerardi*) and the short form of *S. alterniflora*. This pattern of vegetation zonation results from a combination of plant competition and the physical characteristics of the intertidal zone. The tall form of *S. alterniflora* dominates the low marsh because it is able to tolerate the stress of inundation and low soil oxygen content, whereas high marsh plants are not. In contrast, *S. patens*, *J. gerardi* and the low form of *S. alterniflora* dominate the high zone to the exclusion of low marsh species because of the superior competitive ability of these plants in obtaining below-ground nutrients (Donnelly and Bertness, 2001; Bertness et al., 2002; Bertness and Pennings, 2007).

A number of key climate variables (changes in air temperature, changes in precipitation, changes in storm climatology and wind, and sea level rise) and stressors (invasive species, altered flows, pollutants, land use/land cover changes) may impact this process directly or indirectly. As sea level rises, the dominant vegetation of the low marsh, the tall form of *S. alterniflora* traditionally restricted to the low marsh zone by competition, can invade the high

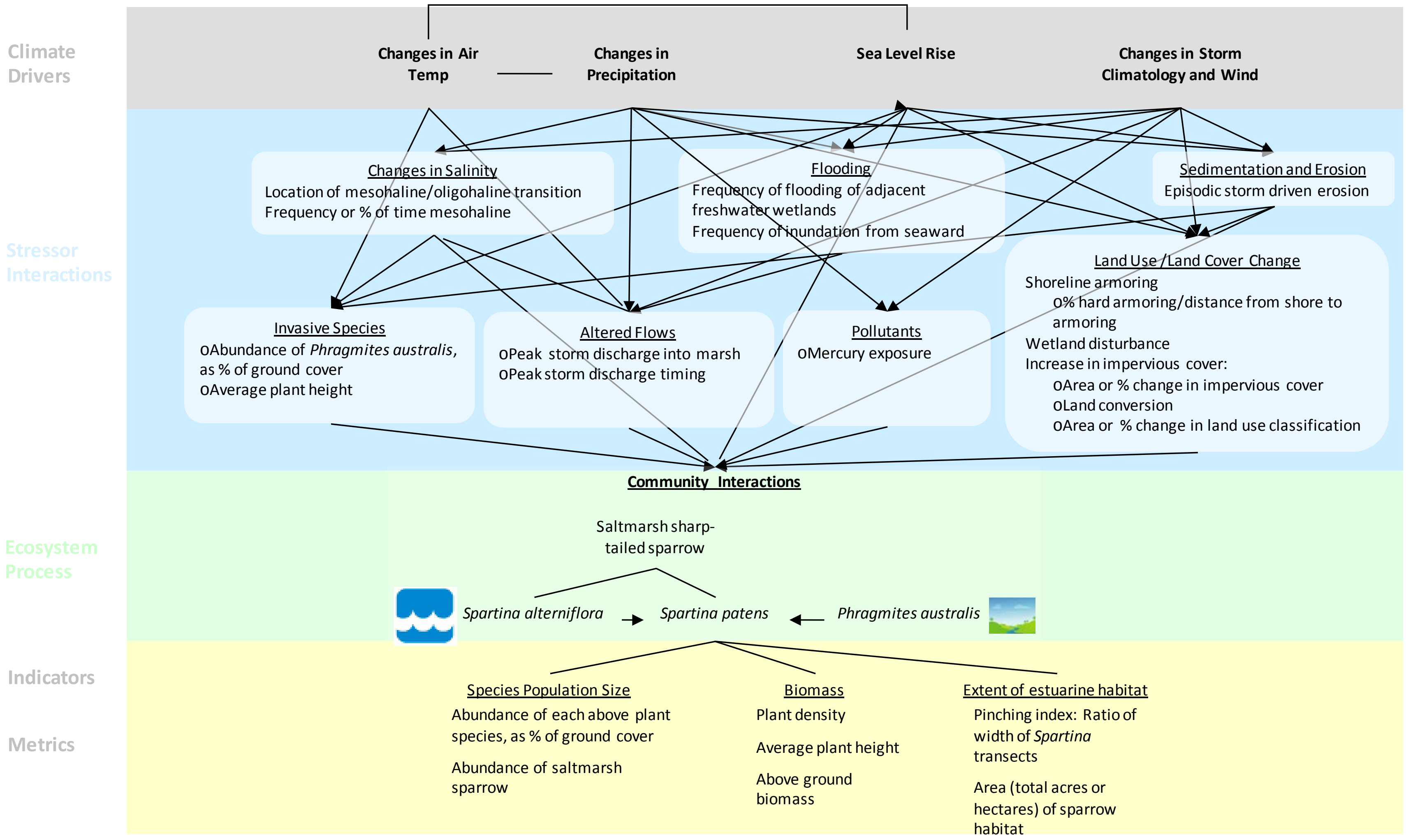


Figure A-3. Community Interactions submodel.

marsh zone because of its tolerance of inundation and salinity. This is already being observed in New England salt marshes (Donnelly and Bertness, 2001). At the same time, the high marsh may be invaded at its landward border by *Phragmites australis* because of nutrient-enrichment from adjacent residential development. This is because high nutrient availability may shift competition away from competition for below-ground nutrients to competition for light. Under these conditions, *Phragmites* is favored over native high marsh plants. Increased nutrient enrichment may also promote invasion of the high marsh at its seaward edge by *S. alterniflora* as it is released from competition for below-ground nutrients (Bertness et al., 2002).

These considerations suggest that the combination of increased sea level rise and nutrient enrichment from residential development may promote invasion of high marsh by *S. alterniflora* at its seaward border and *Phragmites* at its landward border. This could greatly reduce the availability of the traditional high marsh nesting habitat of the Saltmarsh Sharp-Tailed Sparrow.

A.3. CONCLUSIONS

The analysis of available data for potential indicators and of existing models indicated that there was insufficient information available on metrics for the indicators to answer the sensitivity questions of this assessment using quantitative modeling. However, it was also evident that a vast amount of local knowledge was available through consultation with regional experts in the processes of interest. This led to the development of the expert elicitation workshop approach described in Section 2 of this report. The workshop was meant to serve as an opportunity to supplement current knowledge based on background research and examine potential changes that may occur due to climate influences. The conceptual diagrams described above provided the basis for the development of the initial influence diagrams used at the workshop (as described in Section 2 of this report) as well as context for how these ecosystem processes of focus fit with the rest of the ecosystem.

A.4. REFERENCES

Ashton, AD; Donnelly, JP; Evans, RL. (2007) A Discussion of the potential impacts of climate change on the shorelines of the Northeastern USA. Mitig Adapt Strat Glob Change 13(7):719-743. DOI 10.1007/s11027-007-9124-3. Available online at http://mit.whoi.edu/science/GG/coastal/publications/pdfs/AshtonDonnellyEvans_MITI2007.pdf.

Bertness, MD; Ewanchuk, PJ; Silliman, BR. (2002) Anthropogenic modification of New England salt marsh landscapes. Proc Nat Acad Sci 99:1395-1398. Available online at http://www.pnas.org/content/99/3/1395.full.pdf+html?sid=86aaf2b6-c384-4819-85b7-8ce54f0bfe97.

Bertness, MD; Pennings, SC. (2002) Spatial variation in process and pattern in salt marsh plant communities in Eastern North America. In: Weinstein, MP; Kreeger, DA; eds. Concepts and controversies in tidal marsh ecology. New York: Kluwer Academic Publishers; pp. 39−57.

Carlisle, BK; Donovan, AM; Hicks, AL; et al. (2002). A volunteer's handbook for monitoring New England salt marshes. Massachusetts Office of Coastal Zone Management, Boston, MA. Available online at http://www.mass.gov/czm/volunteermarshmonitoring.htm.

Cavatorta, JR; Morgan, J; Hopkinson, C; et al. (2003) Patterns of sedimentation in a salt marsh-dominated estuary. *Biol. Bull.* 205: 239-241. Available online at http://www.biolbull.org/cgi/reprint/205/2/239.pdf.

CCSP (Climate Change Science Program). (2008) Preliminary review of adaptation options for climate-sensitive ecosystems and resources. Synthesis and Assessment Product 4.4. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Julius, SH; J.M. West, JM; eds. Baron, JS; Griffith, B; Joyce, LA; et al (Authors). U.S. Environmental Protection Agency, Washington, DC, USA, 873 pp. http://downloads.climatescience.gov/sap/sap4-4/sap4-4-final-report-all.pdf

DiQuinzio, D; Patona, PWC; Eddlemanac, WR. (2002) Nesting ecology of saltmarsh sharp-tailed sparrows in a tidally restricted salt marsh. Wetlands 22(1):179−185.

Donnelly, J; Bertness, M. (2001) Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. Proc Natl Acad Sci 98:14218−14223. Available online at http://www.pnas.org/content/98/25/14218.full.pdf+html?sid=86aaf2b6-c384-4819-85b7-8ce54f0bfe97.

Frumhoff, PC; McCarthy, JJ; Melillo, JM; et al. (2007) Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions. Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (UCS). Available online at http://www.northeastclimateimpacts.org.

Gjerdrum, C; Elphick, CS; Rubega, M. (2005) Nest site selection and nesting success in saltmarsh breeding sparrows: the importance of nest habitat, timing, and study site differences. Condor 107:849-862.

Kneib, R; Simenstad, C; Nobriga, M; et al. (2008) Tidal marsh conceptual model. Sacramento (CA): Delta Regional Ecosystem Restoration Implementation Plan. Available online at http://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=10093

Massachusetts Office of Coastal Zone Management. (2003) North Shore Wetland Assessment project report: transferring a wetland assessment method to the North Coastal and Ipswich River Watersheds. Report released February 2003. Available online at http://www.mass.gov/czm/ma_czm_wetlandassess_nsreport2003.pdf.

MBP (Massachusetts Bays Program). (1996) Comprehensive conservation and management plan: an envolving plan for action. U.S. Environmental Protection Agency, Massachusetts Executive Office of Environmental Affairs, Boston, MA. Available online at http://www.mass.gov/envir/massbays/ccmp.htm

MBP (Massachusetts Bays Program). (2003) Comprehensive conservation and management plan: an envolving plan for action. 2003 revisions to the CCMP. U.S. Environmental Protection Agency, Massachusetts Executive Office of Environmental Affairs, Boston, MA. Available online at http://www.mass.gov/envir/massbays/pdf/revisedccmp.pdf

MBP (Massachusetts Bays Program). (2009) Massachusetts Bays Program Strategic Plan: April 2009-June 2012. April 1, 2009 Draft. Massachusetts Executive Office of Environmental Affairs, Boston, MA

Nyman, JA; Crozier, CR; DeLaune, RD. (1995) Roles and patterns of hurricane sedimentation in an estuarine marsh landscape. Estuar Coastal Shelf Sci 40(6):665–679.

Orson, RA; Warren, RS; Niering, WA. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuar Coastal Shelf Sci 47(4):419-429.

Reed, DJ. (1995) The response of coastal marshes to sea-level rise: survival or submergence? Earth Surf Proc Landforms 20(1):39–48.

Roman, CT; Peck, JA; Allen, JR; et al. (1997) Accretion of a New England (U.S.A.) salt marsh in response to inlet migration, storms, and sea level rise. Estuar Coastal Shelf Sci 45(6):717–727.

SFEIT (San Francisco Estuary Indicators Team). (2008) Assessment framework as a tool for integrating and communicating watershed health indicators for the San Francisco estuary. Technical Report #1. Submitted by the San Francisco Estuary Indicators Team to the California Department of Water Resources, September 30, 2008.

Schoellhamer, D; Wright, S; Drexler; J; et al. (2007) Sedimentation conceptual model. Sacramento, (CA): Delta Regional Ecosystem Restoration Implementation Plan. Available online at http://science.calwater.ca.gov/pdf/drerip/DRERIP_sediment_conceptual_model_final_111307.pdf

USGS-FWS (U.S. Geological Survey-Fish and Wildlife Services). (2008) Salt marsh assessment study: metrics identified for testing at national wildlife refuges. U.S. Department of the Interior, Washington, DC.

APPENDIX B. EXPERT ELICITATION WORKSHOP PREPARATION AND IMPLEMENTATION

B.1. PREWORKSHOP

B.1.1. Selecting Workshop Participants

The MBP partners developed a list of criteria for selecting highly qualified local experts who spanned the range of disciplines, science and management continuum, and empirical versus theoretical research experience needed to collectively characterize the ecosystem processes under consideration. Criteria for selecting participants included:

- Demonstrated understanding of the body of literature with regard to sediment retention OR community interactions (depending on which breakout group), as evidenced by academic training, research, and publications
- Demonstrated ability to think of uncertainty in qualitative terms
- Knowledge of science behind estuary management, as evidenced by academic training, research, and publications
- Knowledge of estuary management issues as evidenced by academic training, research, and publications
- Past work in MBP region
- Past work with salt marsh development/sediment retention processes (the balance of sediment supply vs. loss) OR salt marsh community interactions (interactions of shorebird nesting habitat and vegetation zonation), depending on the candidate’s proposed breakout group

These criteria were considered in developing a list of 20−24 qualified candidates for each breakout group. Candidates were then contacted to determine their availability and interest in testing a new method for vulnerability assessment. From this larger pool, a group of seven experts was selected for each breakout group. According to EPA’s Expert Elicitation Task Force White Paper (http://www.epa.gov/spc/expertelicitation/index.htm), a review of the literature indicates that 90% of successful expert elicitations use between 3 and 11 experts, with a law of diminishing returns in having a group larger than six. For this study, workshop participants included the following individuals:

Sediment Retention Breakout Group:
Susan Adamowicz, Rachel Carson National Wildlife Refuge
Britt Argow, Wellesley College
Chris Hein, Boston University
David Ralston, Woods Hole Oceanographic Institution
John Ramsey, Applied Coastal Research and Engineering, Inc.
Peter Rosen, Northeastern University
John Teal, Woods Hole Oceanographic Institution

Community Interactions Breakout Group:
Walter Berry, U.S. EPA Atlantic Ecology Division
Robert Buchsbaum, Massachusetts Audubon Society
Dave Burdick, University of New Hampshire
Michele Dionne, Wells National Estuarine Research Reserve
David Johnson, Woods Hole Marine Biological Laboratory
Gregg Moore, University of New Hampshire
Cathy Wigand, U.S. EPA Atlantic Ecology Division

The expertise of each of the individual participants contributed to the interdisciplinary complexity of the group. Experts were selected from the management and adaptation research communities, and represented federal and state government agencies, research and consulting organizations, nongovernmental organizations and academia. The credentials for each of the participants, including past and current work and research and areas of expertise, are summarized for the Sediment Retention group in Table B-1, and for the Community Interactions group in Table B-2.

B.1.2. “Straw Man” Influence Diagrams

An initial “straw man” influence diagram (see Figure B-1 and Figure B-2) for each breakout was developed by ICF, EPA, and MBP prior to the workshop based on the more detailed salt marsh conceptual model and sediment retention and community interactions submodels developed previously (see Appendix A). The “straw man” influence diagrams differed from the more comprehensive conceptual models in that they focused on only those elements of the model that participants believe are most critical for understanding responses of the ecosystem process to the human and climate stressors under consideration. The “straw man”

Table B-1. Sediment Retention breakout group participants, affiliations, and qualifications

Name	Affiliation	Qualifications
Susan Adamowicz	Rachel Carson National Wildlife Refuge	U.S. Fish and Wildlife Service Land Management Research Demonstration Biologist. Expertise in salt marsh ecology, habitat management, restoration, and tipping points.
Britt Argow	Wellesley College	Research on salt marsh and estuarine sedimentology, geomorphology, and hydrology. Expertise in geosciences and coastal sedimentology.
Chris Hein	Boston University	Research on inorganic sediment processes in coastal systems. Expertise in coastal sedimentology.
David Ralston	Woods Hole Oceanographic Institution	Research on fluid mechanics and scalar transport in estuaries and the coastal systems. Expertise in estuarine physics and sediment transport.
John Ramsey	Applied Coastal Research and Engineering Inc.	Serves on Climate Change Adaptation Advisory Committee for Massachusetts, and has provided consulting on coastal engineering projects. Expertise in coastal processes and engineering.
Peter Rosen	Northeastern University	Research on coastal processes, geomorphology and sedimentology. Developing a model for the evolution of Boston Harbor Island shorelines in response to rising sea levels. Expertise in coastal geology.
John Teal	Woods Hole Oceanographic Institution	Research and consulting on coastal wetlands, salt marsh restoration, submerged aquatic vegetation, and nutrients. Currently involved with marsh restoration in fresh, brackish and salt wetlands. Expertise in wetlands ecology.

Table B-2. Sediment Retention breakout group participants, affiliations, and qualifications

Name	Affiliation	Areas of expertise
Walter Berry	U.S. EPA Atlantic Ecology Division	Research on human disturbance impacts on avian species. Expertise in salt marsh ecology.
Robert Buchsbaum	Massachusetts Audubon Society	Directs Massachusetts Audubon's Ecological Inventory and Monitoring Project. Research on coastal plant and animal species, nutrients, and climate change. Expertise in salt marsh ecology.
Dave Burdick	University of New Hampshire	Research on salt marsh restoration, invasive species, and tidal restoration. Recent research on *Spartina patens* and *Phragmites australis*. Expertise in restoration ecology.
Michele Dionne	Wells National Estuarine Research Reserve	Research on aquatic habitats, marsh-estuarine food web ecology, and wetland restoration. Established monitoring protocols for restoration projects in the New England region. Expertise in aquatic, coastal, and salt marsh ecology.
David Johnson	Woods Hole Marine Biological Laboratory	Research on aquatic species, nutrients, and salt marsh habitat. Recent study on salt marsh infauna and nutrient enrichment in Plum Island. Expertise in salt marsh and invertebrate ecology.
Gregg Moore	University of New Hampshire	Research on aquatic species, restoration ecology, invasive species, and plant zonation. Recent project comparing natural vs. tidally restricted salt marshes in Cape Cod. Expertise in coastal wetland ecology.
Cathy Wigand	U.S. EPA Atlantic Ecology Division	Research on plant species, nutrients, and human disturbance impacts on salt marshes in New England. Expertise in wetland ecology.

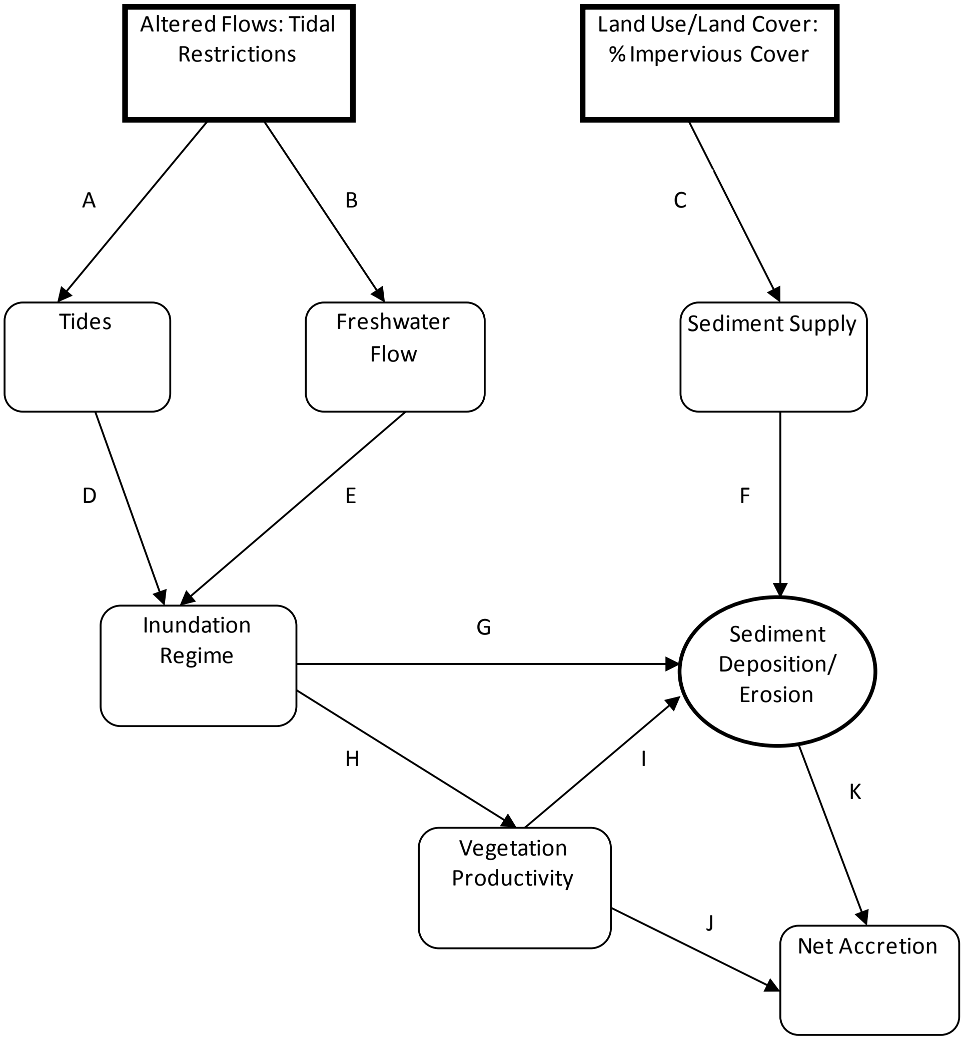


Figure B-1. Sediment Retention "straw man" influence diagram.

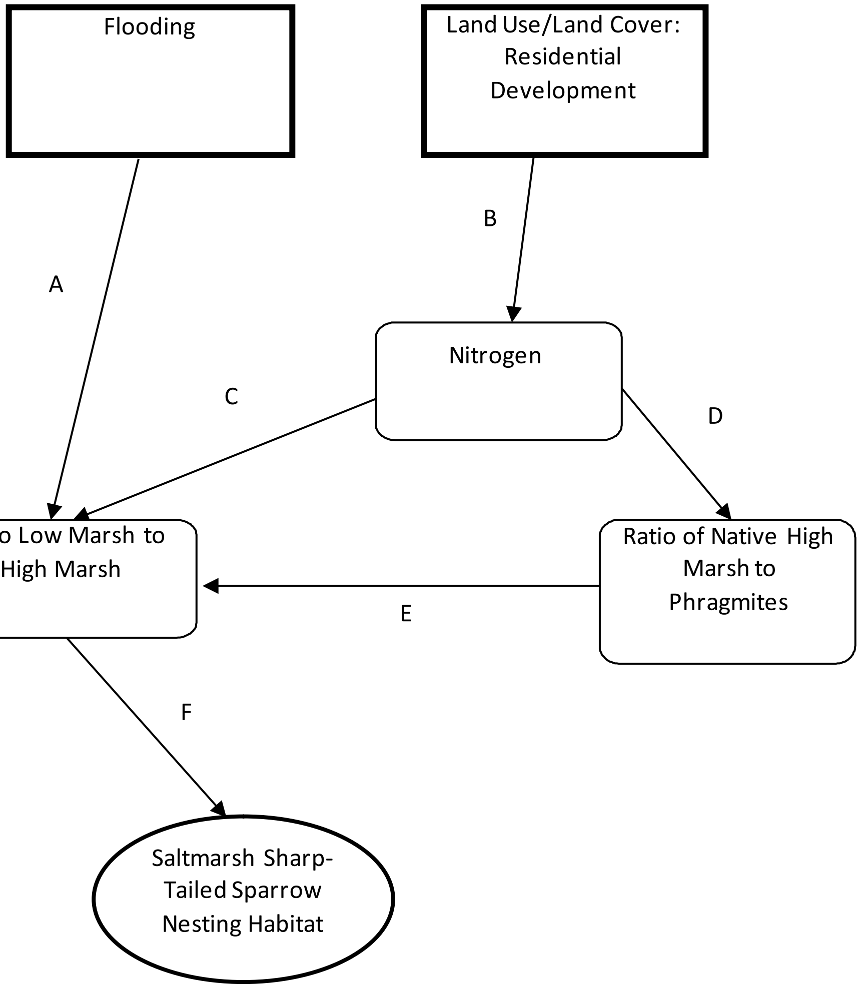


Figure B-2. Community Interactions "straw man" influence diagram.

influence diagrams were used in the preworkshop briefing and homework assignment in order to further refine the sediment retention and community interactions influence diagrams.

B.1.3. Preworkshop Briefing and Homework Assignment

Participants participated in two preworkshop briefing calls and a homework assignment that would be used to develop consolidated influence diagrams to be used at the workshop. The preworkshop briefing calls were held on January 14 and 28, 2010. These calls gave participants a briefing on the background of the project, work to date, the purpose of the workshop, and an overview of the homework assignment. The first call covered the larger context of the project as part of the CRE Program and the purpose for MBP being involved in this study. The development of the conceptual models (see Appendix A), and how these led to the ecosystem processes of focus was also covered. Finally, the expert elicitation approach was explained in the context of how it would be used for the purposes of the workshop. The second call went into more detail about the exercise, introducing the influence diagrams and example reference site. Participants were given an opportunity to ask questions regarding these initial diagrams in preparation for completing the homework assignment.

Part of the background material presented was information on an example site for participants to consider when more spatial specificity would be useful during the workshop exercise and to provide context for management discussions. The Jeffrey’s Neck or Little Neck Marsh, in Ipswich, Massachusetts, is located within the Great Marsh, and was chosen because it includes classic New England salt marsh features and species composition. Its natural features include the high marsh/low marsh dynamic examined by the Community Interactions group. There is an extensive system of creeks and channels, as well as large areas of bordering vegetated edge and upland. The example site is subject to a number of stressors common to marshes in the region, including: development surrounding the marsh; tidal restrictions (this particular site has two, one of which that has been restored); a significant amount of invasive *Phragmites*; extensive mosquito ditching; and other hydrologic modifications such as road crossings and barriers to migration.

The homework assignment asked participants to review a number of items: (1) selected articles relevant to the ecosystem process breakout group to which they were assigned (for the Sediment Retention breakout group: Cavatorta et al. [2003]; Donnelly and Bertness [2001]; Scavia et al. [2002]; Schmitt et al. [1998]; for the Community Interactions breakout group: Bertness et al. [2002]; DiQuinzio et al. [2002]; Donnelly and Bertness [2001]; Gjerdrum et al. [2005]; and Scavia et al. [2002]); (2) conceptual models of the ecosystem and ecosystem process to which they were assigned; and (3) the draft influence diagram for the ecosystem process to which they were assigned. Participants were asked to review the draft influence diagram and provide recommendations on what should be added or removed. Participants were asked to add or subtract variables or relationships until the preliminary influence diagram matched their understanding of the process. We asked participants to include no more than 10−15 variables in the diagram in order to keep it focused on the highest priority influences. We also asked participants to focus on current conditions (including current climate) when reviewing and commenting on the diagram.

Participants were asked to provide a quantitative definition for each variable, a metric for measuring the variable, and a range of values for the metric. Participants were also asked to assign values to the metrics they selected. This could include actual measured values (e.g., 35 km^3 of inflow) as well as a range of values (e.g., 5 to 50 km^3 of inflow).

B.1.4. Consolidated Influence Diagrams

The preliminary diagram for each breakout group was revised prior to the workshop based on the participants' homework responses. The process involved examining the participants' responses and constructing a tally of the variables used and influences (arrows) included. Variables and influences that were most frequent across all responses were included in the consolidated influence diagrams. For the both the Sediment Retention and Community Interactions groups, all of the participants provided comments on the preliminary influence diagram. In addition, due to the rescheduling of the initial MBP workshop, two of the original participants were not able make the new date, but their homework was taken into account when developing the consolidated diagrams. Based on the responses from the participants, consolidated influence diagrams were developed for the workshop.

B.2. WORKSHOP

B.2.1. Group Influence Diagrams

Group influence diagrams were developed during the first day of the workshop. Within their breakout groups, the participants discussed how the consolidated influence diagrams should be refined for use as a final "group" influence diagram. The participants added, removed, or redefined variables based on a group discussion. The group diagrams were to become the basis for the expert elicitation exercise of assigning judgments about influences among variables. The Sediment Retention and Community Interactions group influence diagrams are provided in Section 2.

B.2.2. Introduction to Climate Scenarios and Confidence

The participants received two handouts designed to orient them to the climate scenarios and to the methodology for assessing confidence. The first handout contained a summary of Climate Scenarios A and B, which was used by the participants in assessing the sensitivity of salt marshes and mudflats across a range of plausible scenarios of climate change. It explained the development of two climate futures in a mid-century (2040−2069) time frame. Participants used these scenarios on Day 2 to make new judgments compared to their judgments under "current conditions" on Day 2. The full climate scenarios handout can be found in Appendix C.

The second handout presented explanatory information and a coding scheme for use by the participants in assessing their confidence in each of their judgments under both current conditions and under Climate Scenarios A and B. The full handout may be found in Appendix D.

B.2.3. Coding Exercise

Following the development of the group influence diagrams, participants were asked to make their individual judgments on the diagram using the coding scheme. As described in Section 2, the participants used the coding scheme to make judgments on the following: (1) type and degree of influence for each relationship included in the influence diagram; (2) the associated confidence for each influence judgment; (3) type of interactive influences for relationships of their own choosing; and (4) the associated confidence for each interactive influence judgment. These judgments were done for current conditions (on the first day of the workshop), and Climate Scenario A and Climate Scenario B (on the second day of the workshop). Example handouts that participants used to make their judgments are provided in Tables B-3, B-4, and B-5.

B.2.4. Variation Across Participants in Sensitivity Judgments

For both the Sediment Retention and Community Interactions groups, variability among participants in their judgments contributed to lack of agreement on sensitivities for some influences. Figure B-3 presents the full range of variation among participants of the Sediment Retention group by showing the same trio of figures as shown in Figure 2-5 but broken out for each individual participant. Looking across all the participants, there was more variability between participants than across scenarios for any given participant. There were no patterns across participants, such as characterizing only increasing sensitivity. The changes across the scenarios made by Participants 3, 6, and 7 were of only increasing sensitivity, and Participants 1, 2, 4, 5 had both increases and decreases, sometimes across the scenarios for one influence.

Table B-3. Example of expert elicitation handout for influences under current conditions (Sediment Retention group)

Instructions: Please assess the effect of X on Y by selecting the appropriate "degree of influence" and its associated "confidence".

	Current conditions					
	Variable X		**Variable Y**	**Degree of influence (please select 0−13)**	**Confidence (LH, LL, HH, HL)**	**Notes**
Relationship A	Land Cover: % Impervious Cover	on	Nutrient Inputs			
Relationship B	Marsh High Water Level	on	Inundation Regime			
Relationship C	Storms	on	Inundation Regime			
Relationship D	Nutrient Inputs	on	Net Accretion			
Relationship E	Nutrient Inputs	on	Below Ground Biomass			
Relationship F	Altered Flows: Tidal Restrictions	on	Tidal Exchange			
Relationship G	Altered Flows: Tidal Restrictions	on	Freshwater Flow			

Table B-4. Example of expert elicitation handout for influences under climate scenarios (Community Interactions group)

Instructions: Please assess the effect of X on Y by selecting the appropriate "degree of influence" and its associated "confidence".

				Climate Scenario A		**Climate Scenario B**		
	Variable X		**Variable Y**	**Degree of influence (please select 0−13)**	**Confidence (LH, LL, HH, HL)**	**Degree of influence (please select 0−13)**	**Confidence (LH, LL, HH, HL)**	**Notes**
Relationship A	OMWM	on	Inundation Regime					
Relationship B	Sea Level	on	Inundation Regime					
Relationship C	Freshwater Flow	on	Salinity					
Relationship D	Freshwater Flow	on	Inundation Regime					
Relationship E	Land Use/Land Cover: Residential Development	on	Freshwater Flow					
Relationship F	Land Use/Land Cover: Residential Development	on	Ratio Low Marsh to High Marsh					
Relationship G	Land Use/Land Cover: Residential Development	on	Ratio of Native High Marsh to *Phragmites*					

Table B-5. Example of expert elicitation handout for interactive influences under climate scenarios (Sediment Retention group)

Instructions: Please assess the effect of X on Y with Z by selecting the appropriate "interactive influence" and its associated "confidence".

						Climate Scenario A		Climate Scenario B		
	Variable X	**on**	**Variable Y**	**with**	**Variable Z**	**Interactive Influence**	**Confidence (LH, LL, HH, HL)**	**Interactive Influence**	**Confidence (LH, LL, HH, HL)**	**Notes**
Example 1: Relationship B+C	Marsh High Water Level	on	Inundation Regime	with	Storms					
Example 2: Relationship G+H	Altered Flows: Tidal Restrictions	on	Freshwater Flow	with	Land Cover: Percent Impervious Cover					

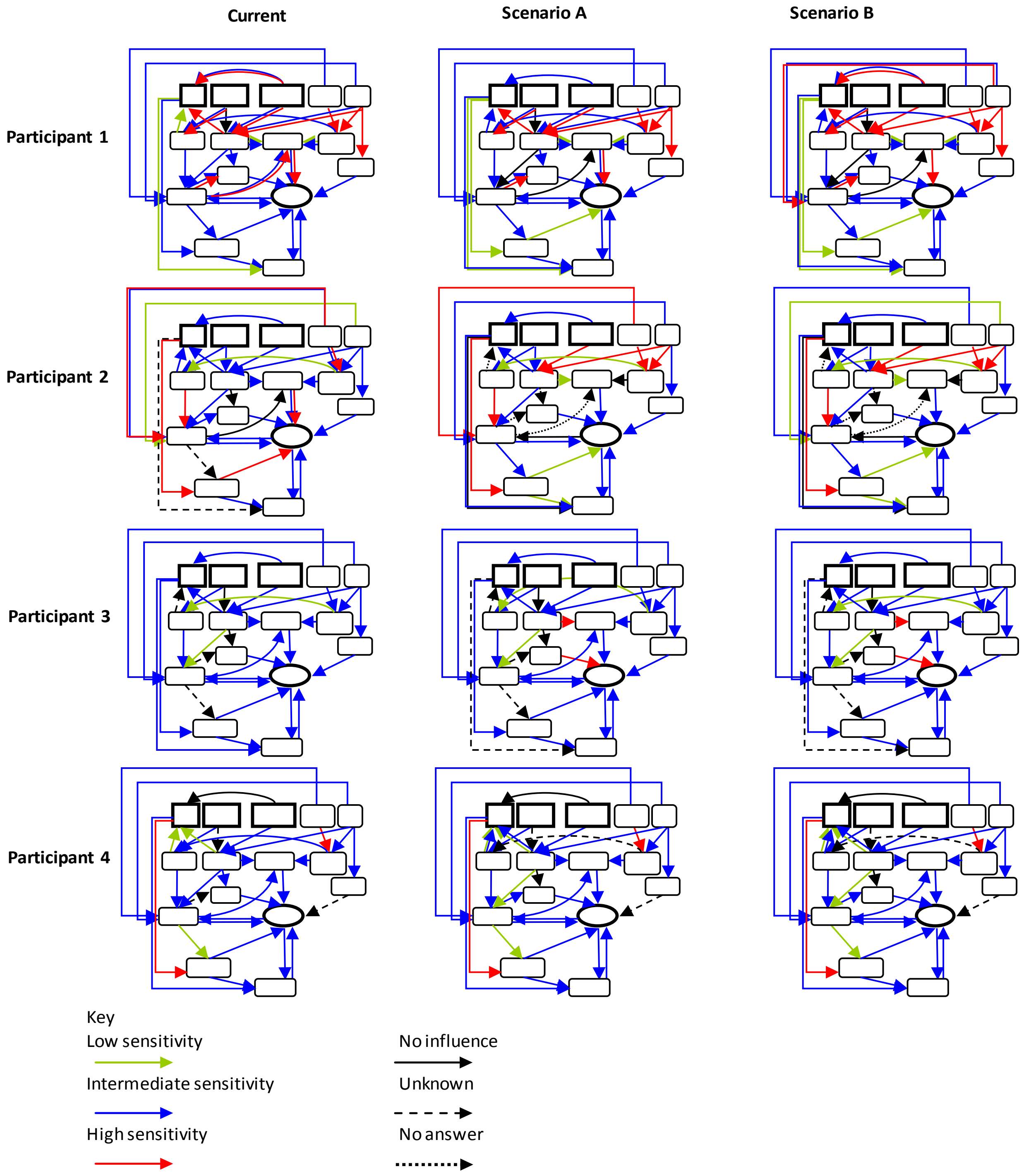


Figure B-3. Sediment Retention group summary influence diagrams of sensitivities: variance across participants.

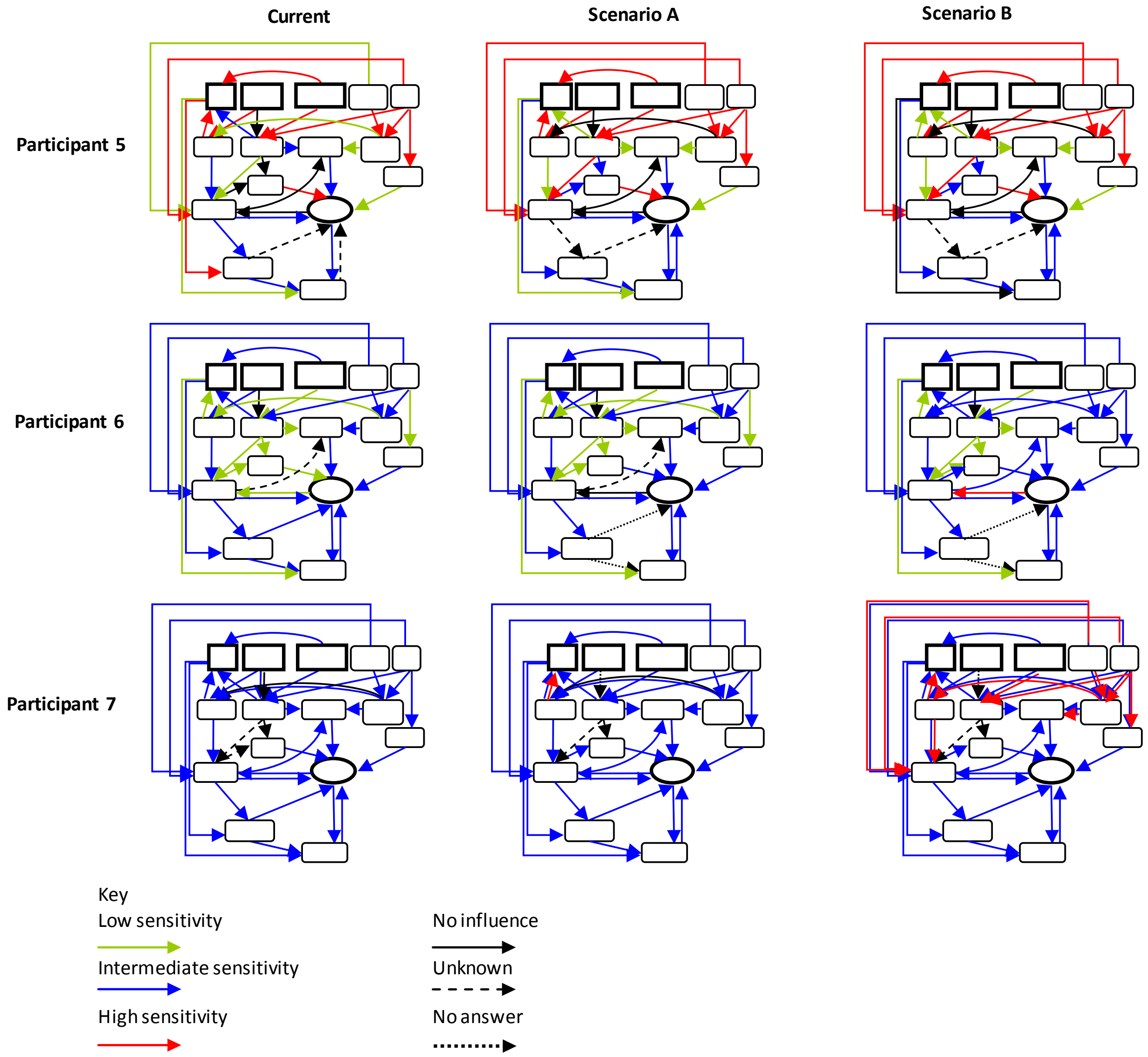


Figure B-3. Sediment Retention group summary influence diagrams of sensitivities: variance across participants. (continued)

For the Community Interactions group, Figure B-4 presents the full range of variation among participants by showing the same trio of figures as those shown in Figure 2-10, but broken out for each individual participant. Looking across all the participants, we see that there is again more variability between participants than across scenarios for any given participant. The majority of changes in sensitivity type across the climate scenarios are of increasing sensitivity. The changes across the scenarios made by Participants 1 are of only increasing

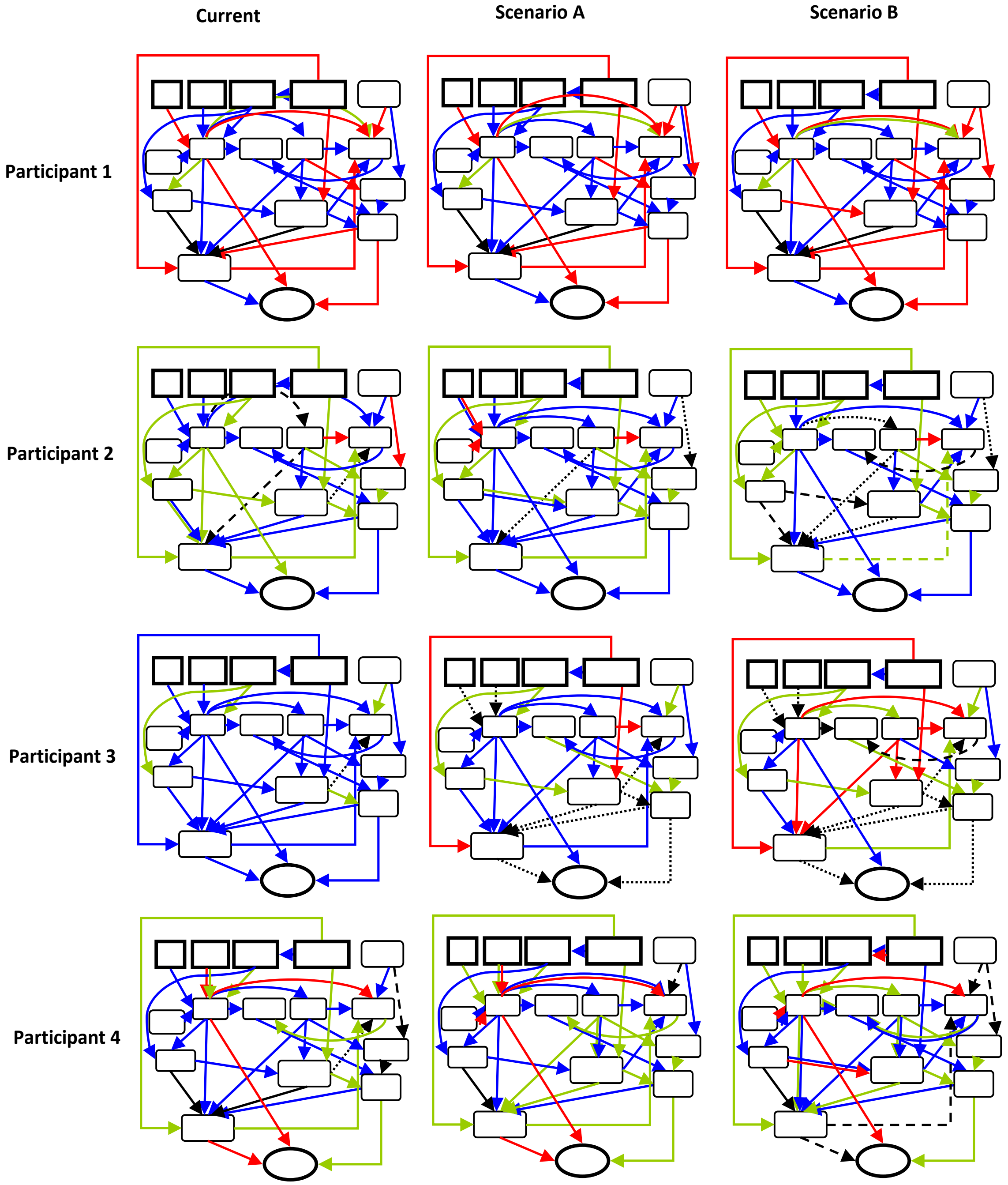


Figure B-4. Community Interactions group summary influence diagrams of sensitivities: variance across participants.

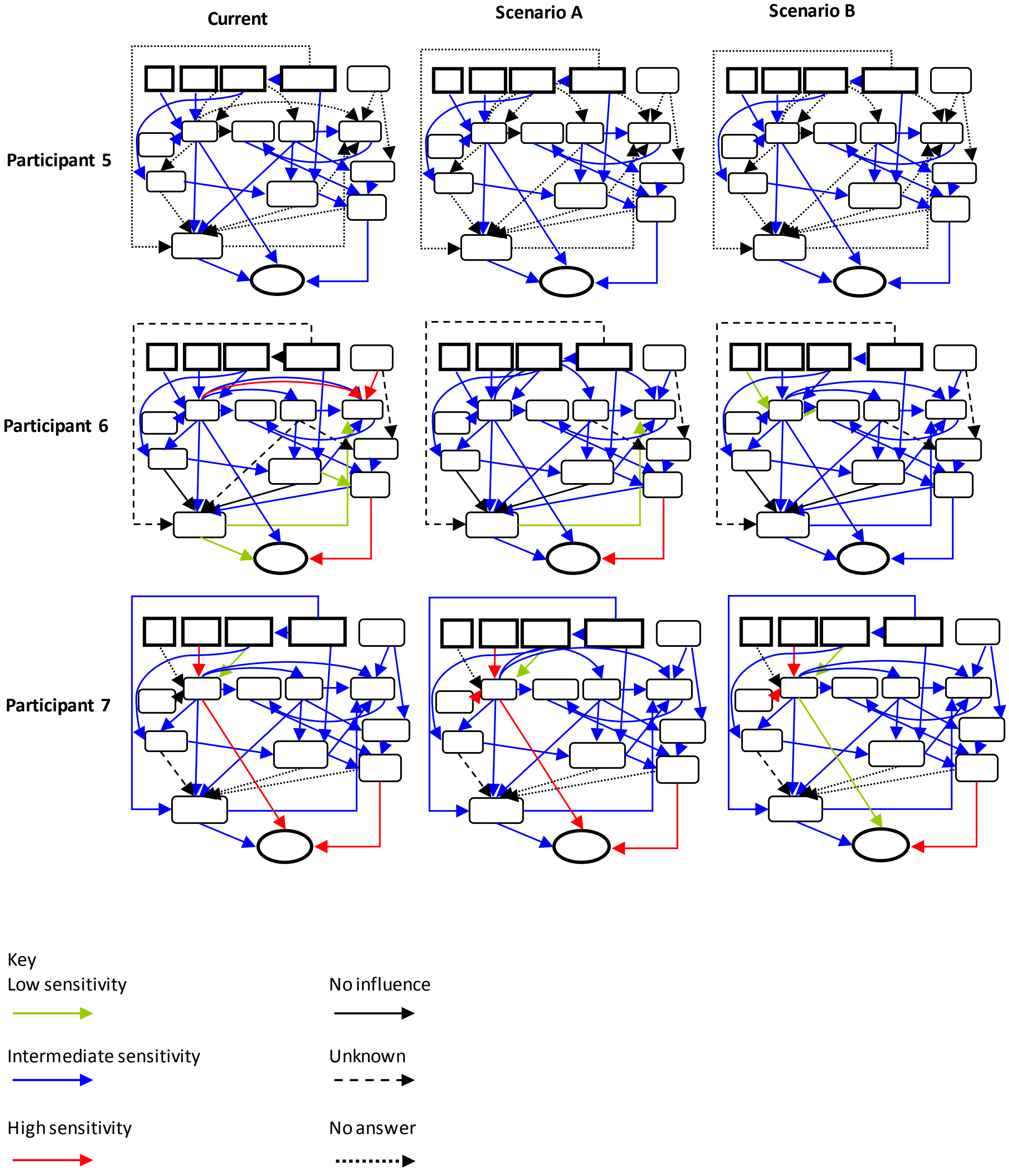


Figure B-4. Community Interactions group summary influence diagrams of sensitivities: variance across participants. (continued)

sensitivity; Participants 2, 3, 4, 6, and 7 had both increases and decreases, but more of the former; Participant 5 had no changes across the scenarios, and only categorized influences as intermediate sensitivity or provided no answer.

B.2.5. Exercise Discussions and Report-outs

After participants made their individual judgments on the influence diagram using the coding exercise, the participants reconvened in their breakout groups for a group discussion. Participants discussed their reactions to the exercise and how it was structured, individual judgments on type and degree of influence, individual judgments on confidence, key issues and gaps in understanding. This group discussion often helped to clarify issues that participants may have had in understanding the coding scheme or understanding influences.

Based on this group discussion, the facilitator helped the participants to identify some key points that emerged. These key points addressed issues such as key influences, important pathways, thresholds, significant changes associated with climate change, management implications, etc. The facilitator from each breakout group presented these key points to the larger group to summarize the discussion.

B.2.6. Discussion of Management Implications

Following the breakout group discussions and exercise of making individual judgments, participants gathered in the larger group to discuss management implications. This discussion would help MBP to examine some of the key issues that emerged from the expert elicitation exercise and how to translate those issues into action. The facilitator led the discussion by asking participants to consider how climate stressors might impact the estuary across a range of management scenarios. The discussion also explored research and data needs, suggestions for habitat restoration and reducing existing stressors, and fundamental shifts in management that may be necessary.

B.3. POSTWORKSHOP

B.3.1. Review of Workshop Report

A report was developed subsequent to the workshop documenting key outputs in two sections: key results and workshop discussions. This report provides a documentation of all of the participant materials, including: participant guidance documents, participant homework responses, handouts and other materials used at the workshop, and individual participant judgments. Key points that emerged during the breakout group and larger group discussions are summarized, as well as the discussion on management implications. Participants were asked to review this report and provide any comments. These comments were incorporated into a final workshop report, which is available upon request from the authors.

B.3.2. Synthesis of Results

A synthesis of results was developed in order to analyze the participants' individual judgments made at the workshop. The synthesis reviews the objectives of conducting the expert elicitation workshop and identifies key questions that the synthesis of judgments seeks to answer. It reviews the coding schemes used by participants during the workshop and summarizes a coding typology that was used to group codes to characterize types and degrees of influences and sensitivities. Finally, it describes the methodology for analyzing the available judgments and presents key results in the form of tables and figures. The contents of this synthesis comprise much of the substance of the results sections of this report.

B.3.3. Review of Draft Report

The workshop report and preliminary results reports were used to develop this technical report to present the synthesis results and place them in the larger context of the implications for management and MBP's capacity to respond. The report will be subjected to a separate letter review, which will be done through an EPA external peer-review process. Following this review, the final report will be developed, which responds to the peer-review comments. An additional report that focuses on lessons learned across the two assessments for San Francisco Estuary Partnership and MBP will also be developed.

B.4. REFERENCES

Bertness, MD; Ewanchuk, PJ; Silliman, BR. (2002) Anthropogenic modification of New England salt marsh landscapes. Proc Nat Acad Sci 99:1395-1398. Available online at http://www.pnas.org/content/99/3/1395.full.pdf+html?sid=86aaf2b6-c384-4819-85b7-8ce54f0bfe97.

Cavatorta, JR; Morgan, J; Hopkinson, C; et al. (2003) Patterns of sedimentation in a salt marsh-dominated estuary. *Biol. Bull.* 205: 239-241. Available online at http://www.biolbull.org/cgi/reprint/205/2/239.pdf.

DiQuinzio, D; Patona, PWC; Eddlemanac, WR. (2002) Nesting ecology of saltmarsh sharp-tailed sparrows in a tidally restricted salt marsh. Wetlands 22(1):179−185.

Donnelly, J; Bertness, M. (2001) Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. Proc Natl Acad Sci 98:14218−14223. Available online at http://www.pnas.org/content/98/25/14218.full.pdf+html?sid=86aaf2b6-c384-4819-85b7-8ce54f0bfe97.

Gjerdrum, C; Elphick, CS; Rubega, M. (2005) Nest site selection and nesting success in saltmarsh breeding sparrows: the importance of nest habitat, timing, and study site differences. Condor 107:849-862.

Scavia, D; Field, JC; Boesch, DF; et al. (2002) Climate change impacts on U.S. coastal and marine ecosystems. Estuaries 25(2):14–164.

Schmitt, C; Weston, N; Hopkinson, C. (1998) Preliminary evaluation of sedimentation rates and species distribution in Plum Island Estuary, Massachusetts. Biol Bull 195(2): 232–233.

APPENDIX C. PARTICIPANT HANDOUT ON CLIMATE SCENARIOS

MBP Workshop Climate Change Scenarios

This handout is intended to assist participants in assessing the sensitivity of salt marshes across a range of plausible scenarios of climate change. It provides the details of two distinct but scientifically credible climate futures for a mid-century (2040-2069) time period. Participants will use these scenarios in revisiting their assessments of influence completed on the first day.

Two Climate Change Scenarios: "Lower-Range" and "Higher Range"[2]

Relatively more mild and more severe mid-century climate change scenarios were selected to bound plausible futures. Overall, both describe a significantly warmer climate accompanied by increases in annual precipitation and higher sea levels, but the degree of change is much greater in the "higher range" compared to the "lower range" scenario. In addition, there are differences in the seasonality of the changes captured in the two futures, particularly as related to precipitation amount and intensity and streamflow.

Development of the Climate Scenarios

These two bounding scenarios were developed directly from the climate projections used in the Northeast Climate Impacts Assessment (NECIA).[3] Three leading climate models were used to develop these projections: U.S. NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1; the United Kingdom Meteorological Office's Hadley Centre Climate Model, version 3 (HadCM3); and the National Center for Atmospheric Research's Parallel Climate Model (PCM). These three models were selected to provide a range of climate sensitivity representative of the current models used by the IPCC.[4] The models were run with both a lower greenhouse gas emission scenario (B1 SRES) and a higher emission scenario (A1Fi SRES) to capture a range of possible future emissions trajectories. The "lower-range" and "higher-range" temperature and precipitation scenarios for 2040-2069 compared to 1961-1990 baseline conditions were developed by averaging the three climate models' results for the lower and higher emissions futures, respectively, and then statistically downscaling these results to the 1/8-degree grid representative of the Ipswich, MA area. Sea level rise information was based on two of the scenarios used in an application of the Sea Level Affecting Marshes Model (SLAMM 5.0) to the Parker River National Wildlife Refuge[5], an area which included the example Jeffrey's Neck Marsh. The "lower-range" eustatic sea level rise scenario is based on the conservative IPCC mean A1B SRES, and the "higher-range" eustatic sea level rise scenario is the mid-century rise for a project 1.5 m rise by 2100, consistent with estimates provided by Rahmstorf (2007).[6,7]

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[2] The usage of the terms "lower-range" and "higher-range" refers to the scenarios provided in this handout and are not intended to reflect the lowest and highest possible futures.

[3] As described in NECIA (2006) and at http://www.northeastclimatedata.org/.

[4] "Climate sensitivity is the temperature change resulting from a doubling of atmospheric carbon dioxide concentrations relative to pre-industrial times" (NECIA 2006).

[5] Clough, J. and E. Larsen. 2009. Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Parker River, Monomoy, and Mashpee NWRs. Obtainable from: Dr. Brian Czech, Conservation Biologist, U. S. Fish and Wildlife Service National Wildlife Refuge System, Division of Natural Resources and Conservation Planning, Conservation Biology Program, 4401 N. Fairfax Drive - MS 670 Arlington, VA 22203.

[6] Rahmstorf (2007) derived a historical semi-empirical relationship between temperature and sea level rise and applied this relationship to IPCC projected estimates of temperature rise.

Summary of Climate Scenarios: Averages for 2040-2069 compared to 1961-1990

		"Lower Range" Scenario (3-model average of B1)	**"Higher Range" Scenario (3-model average of A1Fi)**
Temperature	Annual Average	**+3.6 °F**	**+5.6 °F**
	Geographically	**Boston "moves" to Philadelphia, PA**	**Boston "moves" to Washington, DC**
	Days > 90 °F[8]	**20 days**	**34 days**
	Coldest Day of Year	**+4.3 °F**	**+6.5 °F**
	Growing Season	**+3 weeks**	**+4 weeks**
Precipitation	Winter Change	**+10.6%**	**+15.1%**
	Summer Change	**+7.9%**	**+11.2%**
	Spring Change	**+15.0%**	**+14.1%**
	Fall Change	**+1.9%**	**-2.2%**
	Heavy Events	**~8% increase in the max amount of precip to fall within a 5-day period**	**~12.5% increase in the max amount of precip to fall within a 5-day period**
	Yearly Snow Depth	**-9 cm**	**-11 cm**
Sea Level	Total Increase	**17 cm** (A1B scenario)	**41 cm** (mid-century model estimate using 1.5 m scenario by end of century) [9]
Storms/Wind	NECIA (2006) suggests little change in the frequency of winter-time storms for the East Coast. However, under the "higher range" scenario, between 5 and 15% of these storms (an additional 1 storm per year) will move northward during late winter (Jan, Feb, March), affecting the Northeast. (No change for the "lower range" scenario.) In addition, the impact of a higher sea level will increase the likelihood of storm damage to coastal locations. For hurricanes, the most current understanding is that rising sea surface temperatures will increase evaporation, increasing the amount of rainfall associated with any given hurricane, but there is too much uncertainty in projections of hurricane frequency and wind intensity to say much about future trends.		

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[7] Note that these projections do not account for changes in dynamic sea level rise or changes in land elevation through subsidence or uplift. For example, by the end of the century, Yin et al. (2009) suggest changes in sea level rise resulting from ocean circulation could be of the same order in magnitude as the eustatic sea level rise estimates for the Boston area.

[8] Compared to the 1960-1990 annual average of 9 days with temperatures above 90°F.

[9] The total difference in range between mean and spring tides of 1.3 ft (39.6 cm) is very close to the higher emission scenario rise of 41 cm. Based on data for Plum Island Sound (south entrance), the spring high tide is generally 0.65 feet (19.8 cm) higher than the mean high tide. http://tidesandcurrents.noaa.gov/tides10/tab2ec1b.html#8.

What else do these changes mean for our system?

	"Lower Range" Scenario (3-model average of B1)	"Higher Range" Scenario (3-model average of A1Fi)
Ice-out	2 weeks earlier	4 weeks earlier
Spring peak flow period	7 days earlier	10 days earlier
Summer low flow period	1 week longer	2 weeks longer
Drought[10] frequency	2 every three years (compared to 1 every 2 years today)	
Winter flooding events	2-fold increase in number of events	
General increases in salinity of estuarine waters, freshwater tributaries, and coastal aquifers during summer		

Where can I find additional information?

The Northeast Climate Impacts Assessment (NECIA) was conducted in 2006/2007. Statistically downscaled climate projections results are discussed in the report, Climate change in the U.S. Northeast. The report and information is available at www.northeastclimateimpacts.org and www.climatechoices.org/ne. The data presented in the scenarios above is available at the NECIA website (www.northeastclimatedata.org).

The U.S. Global Change Research Program (USGCRP) developed another set of climate projections through statistical downscaling of climate models and provides regional summaries of projected changes in climate and the potential impacts in the publication, Global Climate Change Impacts in the United States. This data is also available online at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html.

Works Cited

Northeast Climate Impacts Assessment (NECIA). 2006. Climate change in the U.S. Northeast: A Report of the Northeast Climate Impacts Assessments. Union of Concerned Scientists, Cambridge, MA.

Rahmstorf, S. 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. Science 315(5810):368-370.

USGCRP. 2009. Global Climate Change Impacts in the United States, Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson, (eds.). Cambridge University Press, 2009.
Yin, J., M. E. Schlesinger and R. J. Stouffer, 2009. Model projections of rapid sea-level rise on the northeast coast of the United States. Nature Geosci, 2(4), 262-266. doi: 10.1038/ngeo462.

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[10] Defined as the monthly soil moisture is more than 10% below the long-term mean (relative to historic simulations).

APPENDIX D. PARTICIPANT HANDOUT ON CONFIDENCE

Method for Assessing Confidence in Expert Judgments

Characterization of uncertainty is a critical component of assessment science. Thus this workshop exercise includes a component in which the expert participants will assess their current level of scientific confidence in each influence for which they are making a judgment. The aim is to provide information on not only degrees of influence among variables, but also the degree of uncertainty associated with each judgment, given the current state of knowledge in the scientific community.

The design of this analysis is derived from general guidance on uncertainty from recent large assessment efforts such as those of the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Climate Change Science Program (CCSP) [e.g., see Moss and Schneider, 2000; IPCC, 2004; IPCC, 2005; CCSP, 2008; CCSP, 2009]. One fundamental principle is the distinction between uncertainty expressed in terms of "likelihood" of an outcome versus "level of confidence" in the science underlying the finding. Likelihood is relevant when assessing the chance of defined future occurrence or outcome, and involves assigning numerical probabilities to qualifiers such as "probable," "possible," "likely," "unlikely" (CCSP 2009). In contrast, level of confidence refers to the (qualitative) degree of belief within the scientific community that knowledge, models, and analyses are accurate, based on the available evidence and the degree of consensus in its interpretation. We are taking this latter approach.

Each expert is asked to rate his/her confidence in each judgment about degree of influence based on: (1) the amount of scientific evidence that is available to support the judgment; and (2) the level of agreement/consensus in the expert community regarding the different lines of evidence that would support the judgment. These confidence attributes are further described below:

High/low amount of evidence: Is the judgment based on information that is well-studied and understood, or mostly experimental or theoretical and not well-studied? Does your experience in the field, your analyses of data, and your understanding of the literature indicate that there is a high or low amount of information on this influence? Sources of evidence – in order of relative importance – include: 1) peer-reviewed literature; 2) grey literature; 3) data sets; 4) personal observations and personal communications.

High/low amount of agreement: Do the studies and reports across the scientific community, as well as your own experience in the field or analyzing data, reflect a high degree of agreement about the influence, or do they lead to competing interpretations?

Based on the above, levels of confidence in judgments can be sorted into four general categories:

- Well established = high evidence/high agreement (HH);
- Competing explanations = high evidence/low agreement (HL);
- Established but incomplete = low evidence/high agreement (LH);
- Speculative = low evidence/low agreement (LL).

References

CCSP, 2008: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, 873 pp.

CCSP, 2009: *Best practice approaches for characterizing, communicating and incorporating scientific uncertainty in climate decision making.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Morgan, M.G., H. Dowlatabadi, M. Henrion, D. Keith, R. Lempert, S. McBride, M. Small, and T. Wilbanks (Authors)]. Washington, DC, 156 pp.

IPCC, 2004: Workshop on Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and of Options. Working Group I Technical Support Unit, Boulder, Colorado [Manning, M., M. Petit, D. Easterling, J. Murphy, A. Patwardhan, H.-H. Rogner, R. Swart and G. Yohe (eds.)], May 11-13, 2004, National University of Ireland, Maynooth, Co. Kildare, Ireland, 146 pp. Available at: http://ipcc-wg1.ucar.edu/meeting/URW/product/URW_Report_v2.pdf.

IPCC, 2005: Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties, 4 pp. Available at: www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-uncertaintyguidancenote.pdf.

Moss, R. and S.H. Schneider, 2000: Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. In: Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC [Pachauri, R., T. Taniguchi, K. Tanaka (eds.)], World Meteorological Organisation, Geneva, Switzerland, 33-51.